One Ecosystem 11: e200222
doi: 10.3897/oneeco.11.e200222

OPEN ACCESS

Review Article

Characterising roadside ecosystems using the SEEA Ecosystem Condition Typology: towards a core set of biophysical variables

Ziadany Mayoral Solis‡, Clémence Chaudron§, Brunelle Marche‡, Mauricio Camargo‡

‡ Université de Lorraine, ERPI, Nancy, F-54000, France, Nancy, France
§ Université de Lorraine, AgroParisTech, INRAE, SILVA, F-54000, Nancy, France

Corresponding author: Ziadany Mayoral Solis ()

Academic editor: Joachim Maes

Received: 18 May 2026 | Accepted: 25 Oct 2026 | Published: 30 Oct 2026

Citation: Mayoral Solis Z, Chaudron C, Marche B, Camargo M (2026) Characterising roadside ecosystems using the SEEA Ecosystem Condition Typology: towards a core set of biophysical variables. One Ecosystem 11: e200222. https://doi.org/10.3897/oneeco.11.e200222

Abstract

Roadsides represent one of the most extensive anthropogenic networks globally, yet no integrative framework currently supports their systemic ecological characterisation and condition assessment. These areas can mitigate the environmental impacts of roads; yet this potential requires a clearer understanding of their functioning. While the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA-EA) framework and its Ecosystem Condition Typology (ECT) have been applied to coastal, forest and freshwater ecosystems, roadsides remain largely unaddressed within this framework, as they are primarily regarded as extensions of transport infrastructure rather than as distinct ecosystems.

This study presents the first application of the SEEA-ECT to roadside ecosystems, combining a compartmental systems perspective with a systematic literature review for the 1950- 2024 period of 97 peer-reviewed studies. Thirty key biophysical variables are identified and organised across five compartments — air, soil, water, flora and fauna — and classified according to ECT physical, chemical, compositional, structural and functional state classes.

© Mayoral Solis Z et al. This is an open access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Results reveal consistent anthropogenic pressure gradients extending from the road edge outwards, cross-compartment interactions driven by biogeochemical cycling, hydrological dynamics and microtopographic control and the central role of soil and flora as intermediary nodes linking pressures to ecosystem responses. Building on these findings, a preliminary core set of 10 biophysical variables is proposed, combining literature-based prioritisation with considerations of ecological relevance and complementarity across ECT classes. This set provides an initial basis for roadside ecosystem condition monitoring and requires further field validation. This framework offers a transferable and internationally standardised foundation for evidence-based roadside management, ecosystem condition accounting and sustainable infrastructure planning.

Keywords

Adaptive management, biophysical variables, ecological indicators, ecosystem condition assessment, Roadside ecosystem, SEEA Ecosystem Condition Typology, socio-ecosystem, systematic literature review

Introduction

Since the dawn of civilisation, humans have significantly reshaped ecosystems to suit their needs rather than adapting to them. Roads are a key element of transport infrastructure, with approximately 36 million km worldwide (CIA 2020). They provide economic and social benefits (e.g. reduced travel times and improved access), but impose significant environmental costs, diminishing the condition and capacity of natural ecosystems (Tsunokawa and Hoban 1997). Across their life cycle, roads contribute to various environmental impacts, including increased runoff, soil erosion, habitat fragmentation and loss and changes in vegetation structure, all of which threaten biodiversity and disrupt ecosystem functioning (Forman and Alexander 1998, Spellerberg 1998). The extent of impacts, known as the “road-effect zone”, ranges from a few metres to several kilometres, affecting adjacent ecosystems all along the entire landscape (Forman 2000, van Strien and Grêt-Regamey 2025).

With the expansion of road networks, roadsides have emerged as a distinct land-cover type of growing ecological relevance. Roadsides are vegetated edges of variable width located between transport infrastructure and surrounding ecosystems, typically composed of vegetation, bare soil and drainage features such as ditches (Phillips et al. 2020a, Marche et al. 2022). Historically, their management has primarily focused on road-user safety and operational efficiency, often overlooking their ecological functions. Since the 1970s, however, increasing recognition of their ecological value has led to the adoption of more biodiversity-orientated management practices (Blakey et al. 2005, Lucey and Barton 2011, Lange et al. 2023). Despite this shift, roadsides remain insufficiently understood as ecosystems in their own right. They occupy an intermediate and often ambiguous position in ecological research, shaped simultaneously by

infrastructure constraints, management interventions and ecological processes, while supporting significant biodiversity and ecosystem functions.

Most existing research on roadsides focuses on isolated components or processes, such as ditch hydrology, vegetation responses to mowing, pollinator communities or pollutant accumulation (Buchanan et al. 2013, Chaudron et al. 2018). This fragmented perspective limits the understanding of how roadside systems function as integrated ecological units. In reality, the atmosphere, water, soil, flora and fauna components of roadside environments are interconnected through biogeochemical cycles, hydrological processes and biological interactions. These cross-compartment linkages play a critical role in determining ecosystem condition and responses to anthropogenic pressures. However, there is currently no integrative framework that systematically organises these variables and their interactions across compartments in a way that supports ecosystem condition assessment and management. From a practitioner's perspective, roadsides are still largely considered a secondary component of transport infrastructure, with management decisions driven mainly by safety requirements, technical constraints and cost considerations (Marche et al. 2022). This perspective often underestimates their capacity to deliver ecosystem services, such as biodiversity conservation, water regulation and soil stabilisation (Phillips et al. 2020a). Addressing these limitations requires approaches that can integrate ecological complexity into structured and actionable knowledge.

To address these gaps, this study adopts a systemic perspective and frames roadsides as socio-ecosystems, i.e. dynamic systems in which biotic and abiotic components interact under continuous human influence from traffic, maintenance practices and infrastructure configuration (Chapin et al. 2011, Domptail et al. 2013, Hadjibiros 2013, Andersson et al. 2017). The analytical backbone of this approach is the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA), developed by the United Nations and, in particular, its Ecosystem Condition Typology, which organises ecosystem attributes into physical, chemical, compositional, structural and functional classes (Czúcz et al. 2021a, United Nations et al 2021). While the SEEA-EA framework has been applied to coastal, forest and freshwater ecosystems (Dvarskas 2019, Farrell et al. 2021, De Valck et al. 2023, Grover et al. 2023, Maes et al. 2023), it has not yet been used to characterise roadside areas. In this study, it is employed as a structuring framework to guide the identification, organisation and interpretation of ecological variables across compartments, enabling a consistent and systemic characterisation of roadside ecosystems.

The objectives of this study are threefold: first, to identify key variables describing biotic and abiotic roadside compartments based on a literature review; second, to analyse cross-compartment interactions to better understand roadsides as ecosystems; third, to translate these insights into a set of 10 core variables, as a first step towards more operational perspectives that are able to provide information for more ecologically grounded management approaches. Addressing these objectives, the study makes three main contributions: (i) a systemic characterisation of roadside ecosystems grounded in the SEEA EA framework, consolidating 30 key variables with an overview of variation patterns and potential spatial gradients*[1]; (ii) an analysis of cross-compartment

interactions and ecosystem responses to anthropogenic pressures; and (iii) a preliminary operational variable classification framework offering a practical entry point for roadside ecosystem condition assessment, designed to be further validated and refined.

The article is structured as follows: the second section presents the theoretical background; the third section describes the methodology; sections four and five present results and discussion; the sixth concludes with the main contributions and future directions.

Theoretical basis

Dynamic compartmental systems for ecosystems approach

Characterising an ecosystem requires documenting and analysing both biotic and abiotic compartments and their interactions within fundamental ecological processes (Tilman et al. 1997, Odum and Barrett 2005, Chapin et al. 2011). These so-called “compartmental” approaches improve understanding of ecosystem dynamics by enabling detailed analysis of essential ecological interactions, processes and relationships (Hadjibiros 2013, Yackinous 2015, Coskun 2019). They divide ecosystems into functional sub-units, each representing a component or process (Hadjibiros 2013, Coskun 2019). This study focuses on five compartments, including biotic elements (fauna and flora) and abiotic components (water, soil, atmosphere, Chapin et al. (2011)).

Compartments variables: System of Environmental—Economic Accounting —Ecosystem Accounting (SEEA EA)

The System of Environmental-Economic Accounting (SEEA) framework provides a structured approach to ensure a comprehensive understanding of ecosystem functioning

(United Nations et al 2021, Czúcz et al. 2021a), where each compartment can be described through a coherent set of variables capturing its physical, chemical, structural and functional attributes.

This framework introduces the Ecosystem Condition Typology (ECT), categorising ecosystem attributes into six classes: physical, chemical, compositional, structural and functional states and landscape characteristics (United Nations et al 2021, Czúcz et al. 2021a). These classes allow the organisation of biophysical data such as water quality, vegetation cover and species diversity (Czúcz et al. 2017, Vallecillo Rodriguez et al. 2022).

While the SEEA framework was originally developed for ecosystem accounting at regional scales, it also serves as a robust reference for selecting relevant variables and indicators to describe ecosystem processes and assess ecosystem health (Esen and Hein 2020, Maes et al. 2020, Farrell et al. 2021, Campos et al. 2022). In this study, the SEEA-EA framework is not applied for ecosystem accounting purposes *stricto sensu*, but

is used as a conceptual and analytical reference to guide the selection, organisation and interpretation of ecosystem condition variables at the roadside scale. Its role is to provide a coherent structure for integrating biotic and abiotic information across compartments, rather than to produce monetary or physical ecosystem accounts.

The SEEA framework and the guidelines proposed by Czúcz et al. (2021b) emphasise prioritising a concise yet effective set of indicators. Instead of an overly extensive dataset, it is recommended to focus on variables reflecting stocks rather than flows at a given time, particularly those sensitive to human-induced changes. This targeted approach ensures a robust and efficient assessment of ecosystem integrity and resilience.

Accordingly, in this study, the SEEA-EA ECT framework was adapted to organise roadside ecosystem variables across five compartments (Fig. 1), serving both as a classification system and an analytical guide. Variables are grouped according to ECT classes and the documented interactions and feedback amongst compartments provide the basis for a systemic characterisation of the roadside ecosystem (Fig. 1). While the ECT framework includes landscape and seascape characteristics as a sixth class, this study treats landscape context as a boundary condition rather than an internal compartment. The SEEA defines this class as metrics operating at coarse spatial scales that influence local ecosystem condition from outside the ecosystem asset itself, describing mosaics, connectivity and fragmentation patterns rather than internal ecosystem attributes. At the roadside scale, landscape context manifests primarily as a contextual pressure shaping background conditions across all five compartments, including adjacent land-use effects on pollutant levels, species pools and hydrological inputs. It is, therefore, more coherently positioned within the pressure framework of this study than as an analytical compartment.

Materials and Methods

This article employed a systematic literature overview, aimed at providing a synthesis of roadside ecological characteristics, based on peer-reviewed scientific publications (Grant and Booth 2009). This approach enabled a structured summary of the key biophysical components of roadside ecosystems (i.e. air, fauna, flora, soil and water) and the identification of the most representative variables for each compartment of this socio-ecosystem.

Literature search and analytical framework

The literature search strategy was built upon the Ecosystem Conditions Typology (ECT) classes proposed by the SEEA-EA framework, ensuring consistency with recognised ecosystem accounting standards. The use of ECT classes as the backbone of the search strategy was a deliberate methodological choice rooted in the study's systemic perspective. A search strategy built around element-specific terms, such as individual pollutants, species groups or roadside elements, would risk reproducing the compartmentalised, variable-by-variable approach that this study explicitly seeks to

achieve. By structuring searches by ECT state classes, namely physical, chemical, compositional, structural and functional states, the strategy was designed to capture studies that address ecosystem attributes at a meaningful level of organisation, regardless of the specific compartment or element studied. This approach inevitably involves a trade-off: studies focused on highly specific roadside elements without reference to broader state classes may be under-represented in the corpus. This limitation is acknowledged and was partially mitigated through systematic cross-referencing and targeted Google Scholar searches. Following this logic, six search equations were defined, each combining ECT classes with roadside and variable-related keywords (Table 1). Searches were conducted primarily on Web of Science for the 1950-2024 period and complemented by targeted exploration in Google Scholar to ensure broader coverage and inclusion of relevant studies.

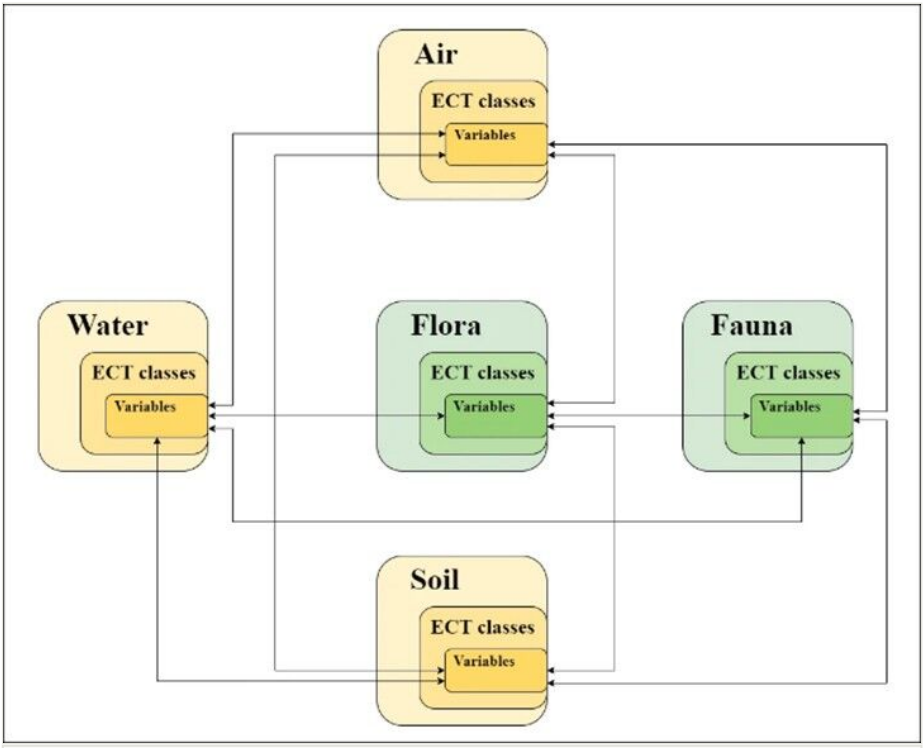


Figure 1.

Concepts for roadside characterisation. Model compartments (air, soil, water, flora and fauna) are described by variables grouped according to the ECT classes from the SEEA framework. Interactions between compartments are explained by variable connections and linked with arrows.

Table 1.
Literature review protocol.

Stage	Strategy	Principle	Description			
Articles' search	Systematic research	Database	Web of Science			
		Type of studies	Journal papers and conference proceedings			
		Period	All years (1950 – 2024)			
		Keywords	"Roadside", "road verge", "right of way", "road edge", "road boundary"			
			"variable", "metric", "indicator", "parameter"			
			"Ecosystem condition typology class"			
		Search equations	**ECT groups**	**ECT class**	**Search equation**	**Records retrieved**
			Abiotic compartments	Physical state	("roadside*" OR "road verge*" OR "right of way" OR "road edge*" OR "road boundar*") AND ("variable*" OR "metric*" OR "indicator*" OR "parameter*") AND ("physic*")	197
				Chemical state	("roadside*" OR "road verge*" OR "right of way" OR "road edge*" OR "road boundar*") AND ("variable*" OR "metric*" OR "indicator*" OR "parameter*") AND ("chemic*")	149
			Biotic compartments	Compositional state	("roadside*" OR "road verge*" OR "right of way" OR "road edge*" OR "road boundar*") AND ("variable*" OR "metric*" OR "indicator*" OR "parameter*") AND ("composition*")	244

Stage	Strategy	Principle	Description			
				Structural state	(“roadside*” OR “road verge*” OR “right of way” OR “road edge*” OR “road boundar*”) AND (“variable*” OR “metric*” OR “indicator*” OR “parameter*”) AND (“structure*”)	339
				Functional state	(“roadside*” OR “road verge*” OR “right of way” OR “road edge*” OR “road boundar*”) AND (“variable*” OR “metric*” OR “indicator*” OR “parameter*”) AND (“function*”)	331
			Landscape level	Landscape	("roadside*" OR "road verge*" OR "right of way" OR "road edge*" OR "road boundar*") AND ("variable*"OR "metric*" OR "indicator*" OR "parameter*") AND ("landscape*")	255
		Total				**1515**
		No duplicates				1079
	Crossing references	Data base	Google scholar			33
Article selection		Criteria	1. Articles contain variables that describe roadsides. 2. Studies focus on biophysical or ecological sciences.			
		Procedure	1. Screening by title and abstract. 2. Scanned introduction, methodology and results. 3. Skimming full article looking at the variable’s information.			
Data extraction				1. Ecosystem compartment 2. ECT class 3. Variables 4. Interactions 5. Special remarks		

Article selection procedure

The selection process followed the PRISMA protocol (Moher et al. 2009) and the recommendations of Siddaway et al. (2019) for systematic reviews (Fig. 2).

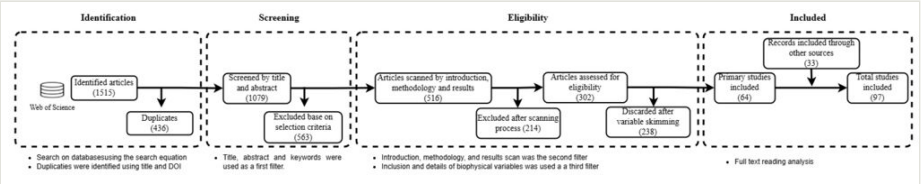


Figure 2.

Schematic representation of the literature review process, adapted from Moher et al. (2009) and Siddaway et al. 2019.

After removing duplicates, 1079 remained from an initial 1515 records. A three-step selection procedure was applied: (i) a first screening, based on title and abstract reading, from which 516 articles were retained; (ii) then, introductions, methodologies and results were scanned to extract the main variables reported, with 302 articles passing this stage; (iii) finally, full texts were skimmed to identify if variables were described, measured or provided data or trends that could be used for the biophysical characterisation of roadsides. At this stage, 238 articles were excluded, leaving 64 articles for detailed analysis (Table 1, Fig. 2). When additional information was needed, reference tracking and cross-searching led to the inclusion of 33 more studies, resulting in a final dataset of 97 articles. Although a landscape-related search equation was initially run and its results were included in the total records retrieved, these articles were systematically excluded during screening, as the variables identified were consistently captured under other ECT classes and operated at spatial scales broader than the roadside unit of analysis.

For each article, the following information was systematically extracted: ecosystem compartment (air, soil, water, flora, fauna), ECT class, variable(s) studied, interactions between compartments and notable remarks or contextual observations (Table 1).

Variable selection criteria

Following Czúcz et al. (2021), selected variables were expected to reflect the intrinsic or functional condition of their compartment and to respond meaningfully to external pressures, ensuring both ***relevance*** and ***sensitivity***. Methodologically, variables were required to accurately measure what they claim to represent and to produce consistent, replicable results across studies, addressing ***validity*** and ***reliability***, respectively. To remain accessible to diverse audiences including practitioners, preference was given to variables that are understandable and, where possible, standardised or widely used in literature, addressing ***simplicity*** and ***compatibility***. Finally, the set of variables as a whole was designed to capture all major ecological dimensions of each compartment

while minimising redundancy, in line with the principles of ***comprehensiveness*** and ***parsimony***.

Dataset overview

From the final corpus of 97 articles, studies were distributed across ecosystem compartments as follows: air (22 studies), soil (20), water (15), flora (30) and fauna (23). Several studies addressed more than one compartment, allowing the identification of cross-compartment relationships. The reviewed studies originate from a wide range of countries. Fig. 3Fig. 3 illustrates their geographic distribution, highlighting both the number of studies per country and the proportional representation of continents within the final corpus. To support the selection of key variables and synthesise the interactions reported in literature, a structured dataset was developed (Suppl. material 1) to organise information on variable–variable interactions and pressure–variable relationships, including major pressure categories such as traffic, landscape context, microtopography, roadside maintenance and road–roadside configuration. This dataset was used to explore patterns of representation in literature and support the development of integrative visualisations.

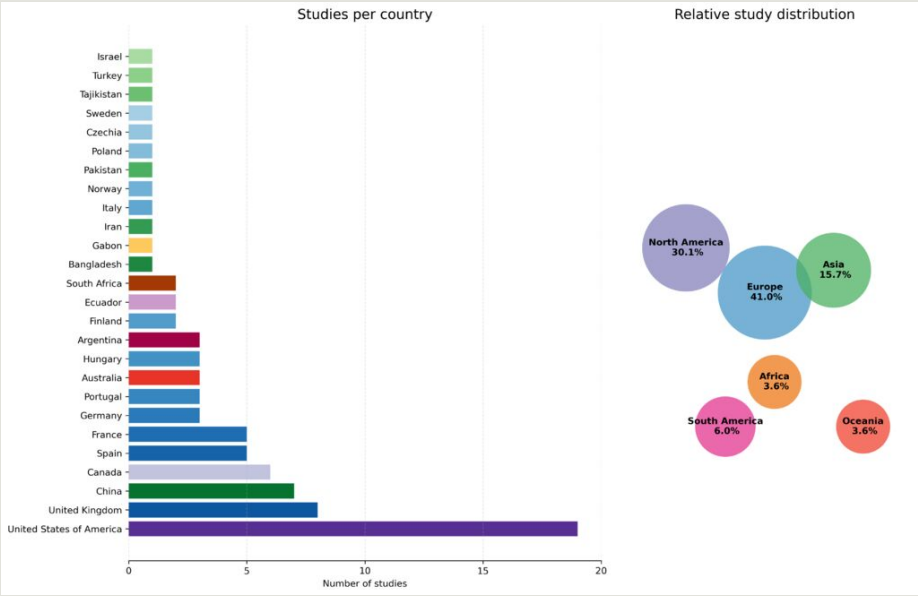


Figure 3.

Geographic distribution of the reviewed studies. The left panel shows the number of studies per country, while the right panel illustrates the percentage of studies per continent. Countries from the same continent are in the same color.

Results

A total of 30 key variables were identified as central to the systemic characterisation of roadside ecosystems. They describe the physical, chemical and biological dimensions of roadside ecosystems (Table 2). These variables encompass both abiotic and biotic dimensions and are organised into ECT classes describing the five ecosystem compartments: air (6 variables), soil (8), water (4), flora (6) and fauna (6), (Table 2). The following subsections present the main findings for each compartment, supported by figures illustrating the general patterns observed across the reviewed studies. Additional details, including specific observations and numerical values, are provided in Suppl. material 2. The final subsection examines the main interactions amongst the identified variables. Given the predominance of studies conducted in temperate regions and industrialised countries, particularly Europe and North America, the reported patterns should be interpreted as general tendencies rather than universally applicable relationships.

Table 2.

Variables describing each roadside compartment by ECT class, retrieved from different references.

ECT Class	Compartment	Variables	References
Physical State	Air	Particulate matter (PM)	Abhijith and Kumar (2020), Aslan et al. (2011), Baldauf (2017), Brantley et al. (2014), Lee and Power (2013), Pasquier and André (2017), Taiwo (2017), Wang et al. (2022) , De Silva et al. (2021)
"	Air	Polycyclic aromatic hydrocarbons (PAH)	Gunawardena et al. (2012), Nikolaeva et al. (2021), Sun et al. (2023), Wang et al. (2022)
"	Air	Heavy metals	Aslan et al. (2011), Gunawardena et al. (2012), Nikolaeva et al. (2021), Lee and Power (2013), Wawer et al. (2015)
"	Soil	Bulk density	Ghosh et al. (2016), Karim and Mallik (2008), McGrath and Henry (2015), Mills et al. (2021), Molina et al. (2024), Zeng et al. (2012)
"	Soil	Texture	Johnston and Johnston (2004), Mills et al. (2021), Nikolaeva et al. (2021), Willmert et al. (2018)
"	Soil	Soil moisture	Hovd and Skogen (2005), Karim and Mallik (2008), Liu et al. (2021), McGrath and Henry (2015), Neher et al. (2013), Nikolaeva et al. (2021)
"	Water	Runoff and water flow	Buchanan et al. (2013), Buchanan et al. (2013), Rudi et al. (2022)
"	Water	Soil sediments	Beschta (1978), Bilby et al. (1989), Forman and Alexander (1998), Kayhanian et al. (2012), Streeter and Schilling (2020)

ECT Class	Compartment	Variables	References
Chemical state	Air	Nitrogen oxides (NOx)	Baldauf (2017), Cape et al. (2004), Chatain et al. (2022), Honour et al. (2009), Lee and Power (2013), Pasquier and André (2017), Peter (1993), Truscott et al. (2005)
"	Air	Ammonia emissions (NH_3)	Cape et al. (2004), Chatain et al. (2022), Lee and Power (2013), Truscott et al. (2005)
"	Air	Greenhouse gases (GHG)	IPCC (2023), McPhillips et al. (2016), Wei and Wang (2020) , Zhu et al. (2022)
"	Soil	pH	Karim and Mallik (2008), Liu et al. (2021), Mills et al. (2021), Neher et al. (2013), Nikolaeva et al. (2021), Truscott et al. (2005), Willmert et al. (2018), Zeng et al. (2012)
"	Soil	Salt content and electrical conductivity	Amrhein et al. (1992), Forman and Alexander (1998), Karim and Mallik (2008), McGrath and Henry (2015), Mills et al. (2021), Molina et al. (2024), Zeng et al. (2012)
"	Soil	Organic matter (OM)	Amrhein et al. (1992), Johnston and Johnston (2004), Karim and Mallik (2008), Liu et al. (2021), McGrath and Henry (2015), Mills et al. (2021), Modlingerová et al. (2012), Molina et al. (2024), Neher et al. (2013), Nikolaeva et al. (2021)
"	Soil	Soil nutrients (NKP)	Jimenez et al. (2013), Johnston and Johnston (2004), Lee and Power (2013), Liu et al. (2021), Neher et al. (2013), Nikolaeva et al. (2021)
"	Soil	Pollutants (Heavy metals)	Budai and Clement (2018), Lee and Power (2013), Liu et al. (2021), Neher et al. (2013), Nikolaeva et al. (2021), De Silva et al. (2021)
"	Water	Pollutants (heavy metals and landscape)	Buchanan et al. (2013), Buchanan et al. (2013), Kayhanian et al. (2012), Lerat-Hardy et al. (2022), McPhillips et al. (2016), Neher et al. (2013), Streeter and Schilling (2020), Tatariw et al. (2021), Zhao and Hazelton (2016)
Compositional State	Flora	Vegetation abundance, richness and diversity	Arenas et al. (2017), Bernes et al. (2017), García-Palacios et al. (2011), Hovd and Skogen (2005), Jakobsson et al. (2018), Karim and Mallik (2008), Monasterolo et al. (2020), Neher et al. (2013), Pourrezaei et al. (2020), Rotholz and Mandelik (2013), Tikka et al. (2001), Truscott et al. (2005), Watkins et al. (2003), Collinson et al. (2019)
"	Flora	Species status (nature value, alien and invasive-alien species)	Arenas et al. (2017), Bernes et al. (2017), Hovd and Skogen (2005), Joly et al. (2011), Kalwij et al. (2008), Lee and Power (2013), Lemke et al. (2019), Motti et al. (2021), Neher et al. (2013), Truscott et al. (2005), Watkins et al. (2003)
"	Fauna	Fauna abundance, richness and diversity	Amatta et al. (2023), Andersson et al. (2017), Delgado et al. (2007), Depalma and Mermoz (2019), Gardiner et al. (2018), Homyack et al. (2014), Homyack et al. (2016), Kroeger et al. (2022), Marsh (2007), Monasterolo et al. (2020), Morelli et al. (2014), Safratowich et al. (2008), Secco et al. (2022), Twerd et al. (2021), Vona-Túri et al. (2017), Wellicome et al. (2014), Collinson et al. (2019)

ECT Class	Compartment	Variables	References
"	Fauna	Species status (nature value, alien and invasive-alien species)	Amatta et al. (2023), Andersson et al. (2017), Depalma and Mermoz (2019), Gardiner et al. (2018), Monasterolo et al. (2020), Vona-Túri (2019)
Functional State	Flora	CSR strategies and nutrient demand	Arenas et al. (2017), Dunnett et al. (1998), Hovd and Skogen (2005), Lee and Power (2013), Truscott et al. (2005)
"	Flora	Leaf attributes and photosynthetic activities	Mehmood et al. (2024), Mehmood et al. (2023), Shahrukh et al. (2023)
"	Flora	Dispersal process	Chaudron et al. (2018), Chaudron and Isselin-Nondedeu (2017), Gelbard and Belnap (2003), Joly et al. (2011), Lemke et al. (2019), Tikka et al. (2001), Vasconcelos et al. (2014)
"	Fauna	Nesting	Depalma and Mermoz (2019), Gardiner et al. (2018), Safratowich et al. (2008), Twerd et al. (2021)
"	Fauna	Food source	Andersson et al. (2017), Gardiner et al. (2018), Kroeger et al. (2022), Monasterolo et al. (2020), Morelli et al. (2014), Vona-Túri et al. (2017)
"	Fauna	Movement	Andersson et al. (2017), DeMers (1993), Homyack et al. (2016), Ji et al. (2017)
Structural state	Flora	Vegetation form and stratification	Depalma and Mermoz (2019), Hovd and Skogen (2005), Karim and Mallik (2008), Lee and Power (2013), Neher et al. (2013), Neher et al. (2017), Truscott et al. (2005), Watkins et al. (2003)
"	Fauna	Distribution	Andersson et al. (2017), DeMers (1993), Galantinho et al. (2017), Galantinho et al. (2020), Homyack et al. (2016), Laurance et al. (2008), Maynard et al. (2016), Ruiz-Capillas et al. (2013)

Roadside air compartment

Roadside environments are marked by unique pollution profiles, resulting from their direct exposure to traffic emissions and proximity to road infrastructure (Pasquier and André 2017). Some pollutants (notably NH_3) also originate from adjacent land uses, such as agriculture (Chatain et al. 2022). However, these pollution profiles are strongly influenced by the presence and structure of roadside vegetation (Brantley et al. 2014, Baldauf 2017). Fig. 4 provides a synthesis of the key variables for the air compartment.

Particulate matter is amongst the most frequently investigated variables in the roadside air compartment, encompassing fractions, such as black carbon, ultrafine particles, $PM_{2.5}$ and PM_{10}. Their concentrations and spatial distributions vary according to particle size and origin, including traffic-related exhaust and non-exhaust emissions (e.g. brake and

tyre wear, road dust re-suspension), regional background*[2] concentrations and secondary aerosol formation (Brantley et al. 2014, Baldauf 2017, Chatain et al. 2022). Black carbon and ultrafine particles typically exhibit pronounced concentration decreases with distance from the road, whereas $PM_{2.5}$ and PM_{10} show weaker or less consistent gradients due to the influence of background concentrations and other sources (Brantley et al. 2014, Pasquier and André 2017, Chatain et al. 2022). These spatial patterns are further influenced by meteorological conditions, particularly wind speed and direction and roadside vegetation, depending on airflow and barrier configuration (Brantley et al. 2014, Baldauf 2017, Pasquier and André 2017, Abhijith and Kumar 2020).

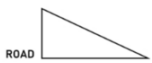
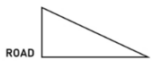
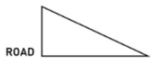
ECT class	Variable	Tendency	Graphic representation	Specifications
Physical state	Particulate matter	Inverse gradient with distance for fine and ultrafine particles		Heavy PM (2.5 and 10) have less consistent gradient patterns
Chemical state	Polycyclic aromatic hydrocarbons	Inverse gradient with distance		Two main traffic sources -exhaust emissions & resuspension
"	Heavy metals	Inverse gradient with distance		Concentrations explained from traffic emissions
"	Nitrogen oxides	Inverse gradient with distance		Concentration increases with traffic volume
"	Ammoniac emissions	Inverse gradient with distance		Higher concentration with traffic intensity
"	Greenhouse gases	Higher concentrations than global averages	—	—

Figure 4.

Synthesis of main variables associated with ECT classes and their general tendencies for the air compartment.

Another air pollutant reported in roadside areas are polycyclic aromatic hydrocarbons (PAH). These compounds can be present in the gas phase (light > 3 benzene rings) or associated with particulate matter (heavy > 4 benzene rings) (Gunawardena et al. 2012). They present an inverse gradient to the road distance. Similarly to particulate matter, PAH concentration decreases when the distance to the road increases (Nikolaeva et al. 2021). Again showing the same inverse gradient with distance from the road, heavy metals are strongly related to traffic emissions (Ni, Cd, Cr, Cu, Zn and Pb; Aslan et al. (2011), Lee and Power (2013), Nikolaeva et al. (2021)). A multi-site study across Europe observed an increase in heavy metal content in roadside shoulders over 12 and 24 months in nearly all sites (Wawer et al. 2015) related to accumulation from traffic emissions.

Regarding ammonia (NH_3) concentrations, they generally follow a decreasing gradient with increasing distance from the road, reflecting traffic-related emissions (Truscott et al. 2005, Chatain et al. 2022). Several studies indicate that ammonia deposition occurs predominantly within the first metres from the road (Cape et al. 2004, Lee and Power 2013, Chatain et al. 2022), clearly impacting roadside air composition. The concentration of nitrogen oxides (NOx) in roadsides can be up to 2.5 times higher than background

levels (Cape et al. 2004, Honour et al. 2009, Chatain et al. 2022). They decrease with distance from the road, but increase with road width (Truscott et al. 2005, Lee and Power 2013). Nitrogen oxides in roadside environments also play a key role in local ozone (O_3) dynamics. Ozone concentrations are not directly addressed in the present analysis, as O_3 is a secondary pollutant and is not emitted directly by traffic sources (Pasquier and André 2017); however, it can contribute to NO_2 concentrations further from the road due to secondary formation.

Studies addressing GHG concentrations along roadsides are limited. Case studies show that carbon dioxide (CO_2; Wei and Wang (2020), Zhu et al. (2022)) and methane (CH_4; Wei and Wang (2020)) concentrations are higher than worldwide averages reported by the Intergovernmental Panel on Climate Change (IPCC 2023). In addition, McPhillips et al. (2016) suggested that roadside ditches generate GHG emissions, such as CH_4, N_2O and CO_2.

Roadside soil compartment

Roadside soils are highly transformed by human activities, including traffic compaction, de-icing treatments and pollutant deposition. These pressures modify soil physical and chemical characteristics at the roadside. Fig. 5 provides a synthesis of the key variables of this compartment.

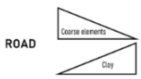
ECT class	Variable	Tendency	Graphic representation	Specifications
Physical state	Bulk density	Inverse gradient with distance		Variations across microtopographic elements, related to road construction and maintenance
"	Soil texture	Inverse gradient for coarse elements near the road Positive gradient for clay particles		Related to soil alteration during road construction and winter road maintenance
"	Soil moisture	Gradient with microtopography		Microtopography influences
Chemical state	Organic matter	Positive gradient with distance		Road disturbance actions
"	pH	Inverse gradient with distance		Values between neutral to basic, explained by winter raod maintenance actions
"	Salt content & electrical conductivity	Inverse gradient with distance		Explained by de-icing salts application in winter
"	Soil nutrients (nitrogen, potassium, phosphorus)	Positive gradient with distance		Runoff influences in nutrient transport
"	Pollutant concentrations(heavy metals)	Inverse gradient with distance		Related to traffic and vehicle wear particles

Figure 5.

Synthesis of main variables associated with ECT classes and their general tendencies for the soil compartment.

Studies consistently indicate that roadside soils are more compacted than background soils, with compaction generally decreasing with distance from the road (McGrath and Henry 2015, Ghosh et al. 2016, Willmert et al. 2018). Additionally, subsurface soil is generally more compacted than surface roadside soils (McGrath and Henry 2015, Molina et al. 2024). These patterns may be attributed to road construction and maintenance activities (Willmert et al. 2018). Soil texture is another variable strongly influenced by road construction and winter maintenance (Willmert et al. 2018). Soils near the road tend to have higher proportions of sand and coarse particles (Nikolaeva et al. 2021, Mills et al. 2021), whereas clay content increases with distance from the road (Johnston and Johnston 2004), reflecting a gradual transition towards the texture of the surrounding environment. Soil moisture varies with roadside microtopography (Hovd and Skogen 2005, McGrath and Henry 2015, Liu et al. 2021), with higher moisture levels reported in ditches and lower levels on shoulders (Karim and Mallik 2008). Additionally, soil moisture has been reported to increase with roadside age (Zeng et al. 2012). Roadside soils generally exhibit low organic matter (OM) content, which tends to increase with distance from the road (Karim and Mallik 2008, Mills et al. 2021). This pattern may be explained by road-related disturbances (Johnston & Johnston 2004). This is relevant since OM can potentially immobilizse toxic elements by binding ions and reducing their mobility in the soil (Amrhein et al. 1992, Modlingerová et al. 2012). Furthermore, studies report a clear influence related to road maintenance practices in temperate zones during winter, such as the application of de-icing salts and sand to maintain road conditions (Amrhein et al. 1992, Neher et al. 2013, Willmert et al. 2018). Studies generally report decreasing gradients in soil salt content, electrical conductivity (Forman and Alexander 1998, Mills et al. 2021, Nikolaeva et al. 2021) and pH with increasing distance from the road (Karim and Mallik 2008, Liu et al. 2021, Mills et al. 2021). Roadside soil pH is generally reported within the neutral to slightly basic range (Truscott et al. 2005, Neher et al. 2013, Willmert et al. 2018), whereas salt content and electrical conductivity are more site-dependent. For instance, reversed salinity gradients have been reported in saline environments (Zeng et al. 2012). Additionally, runoff can wash salts out of roadside soils and reduce electrical conductivity (McGrath and Henry 2015). Roadside soils show a strong gradient in nutrient concentration and road distance, reflected in different values across distinct microtopographic elements. Nitrogen and phosphorus concentrations tend to increase with distance from the road, while potassium exhibits more variable patterns (Johnston and Johnston 2004, Liu et al. 2021, Mills et al. 2021). This pattern could be related to runoff influences in nutrient transport along roadside areas as well as influences from the surrounding landscape (Johnston and Johnston 2004, Mills et al. 2021). Topography can further influence nutrient patterns, as shown by Jimenez et al. (2013) where nitrogen was higher on downhill embankments compared with uphill road cuts, while potassium displayed the opposite tendency. Heavy metals are the most frequently investigated pollutants in roadside soils, with concentrations generally decreasing with distance from the road (Lee and Power 2013, Neher et al. 2013, Nikolaeva et al. 2021). Their accumulation is primarily associated with traffic-related sources, including vehicle component wear (e.g. brakes and tyres) and road surface particles (Neher et al. 2017, Budai and Clement 2018, Nikolaeva et al. 2021). Higher traffic intensity is also

associated with increased heavy metal concentrations in roadside soils (Lee and Power 2013, Liu et al. 2021).

Roadside water compartment

Roads significantly influence hydrological systems, primarily through alterations to stream paths and flow rates (Forman and Alexander 1998, Buchanan et al. 2013). Ditches constructed parallel to roads are designed to evacuate water from road surfaces efficiently, but they also modify runoff patterns, increase erosion, facilitate sediment and pollutant transport and alter watershed hydrology by affecting both water levels and water quality. Fig. 6 synthesises the key variables for the water compartment.

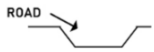
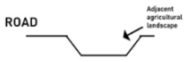
ECT class	Variable	Tendency	Graphic representation	Specifications
Physical state	Runoff & water flow	High flow rates in roadside ditches	—	Rates are higher than in natural streams and agricultural ditches
"	Soil sediments	Strongly present in roadside ditches	—	—
Chemical state	Water pollutants: heavy metals	Concentration depends on drainage, rainfall, antecedent dry periods, and traffic		Higher concentration with more traffic circulation
"	Water pollutants: landscape pollutants	Come from adjacent agricultural land use		Short residence times reduce their degradation; this may impact downstream water bodies' quality

Figure 6.

Synthesis of main variables associated with ECT classes and their general tendencies for the water compartment.

Road ditches modify hydrological dynamics by accelerating water drainage and intercepting groundwater and shallow interflow, potentially increasing downstream flood risks, while lowering local water tables and soil moisture levels (Buchanan et al. 2013, Buchanan et al. 2013). Ditch vegetation management also influences water transport, with mowing associated with increased hydraulic resistance and reduced water conveyance capacity in vegetated agricultural ditches (Rudi et al. 2022). Increased runoff associated with road infrastructure can further promote soil erosion and sediment transport into roadside ditches and downstream waterbodies, depending on road characteristics, land use and topographic conditions (Beschta 1978, Bilby et al. 1989, Forman and Alexander 1998, Kayhanian et al. 2012). However, roadside ditches can also contribute to sediment retention, potentially improving downstream water quality (Streeter and Schilling 2020).

Beyond hydrological impacts, roadside water quality is influenced by pollutants originating from two main sources: road infrastructure and traffic and surrounding land use. Road-related pollutants originate from vehicle and road component wear, oil and fuel leaks, accidental spills and maintenance activities (Ramísio et al. 2021), whereas surrounding land use contributes pollutants, such as agrochemicals from agricultural

areas (Kayhanian et al. 2012, Buchanan et al. 2013). In the reviewed literature, heavy metals were the main road- and traffic-related pollutants investigated, while agricultural pollutants were the most frequently documented pollutants associated with surrounding land use. Short water residence times in roadside ditches may limit pollutant degradation compared with natural stream networks, potentially affecting downstream water quality. Nevertheless, vegetated roadside ditches can contribute to nutrient removal and improve water quality (McPhillips et al. 2016, Neher et al. 2017, Streeter and Schilling 2020, Tatariw et al. 2021).

Roadside flora compartment

Roadside maintenance practices directly influence vegetation composition and structure, particularly through interventions aimed at maintaining road visibility and safety. A synthesis of the key variables for the flora compartment is presented in Fig. 7.

ECT class	Variable	Tendency	Graphic representation	Specifications
Compositional state	Vegetation abundance, richness, and diversity	Higher richness than adjacent fields	—	Influenced by management practices, landscape, roadside, and road characteristics
"	Species status (nature value, alien & invasive alien species	Habitats for protected and grassland species Can be prone to invasive species proliferation	—	—
Functional state	CSR (competitor, stress-tolerator,ruderal) strategies and nutrient demand	Nutrient-demanding and ruderal species are dominant near the road		—
"	Leaf attributes and photosynthetic activity	Species present reduced photosynthetic activities	—	Air pollutants strongly influence plant stomata activity
"	Dispersal process	Traffic and management activities influence plant dispersion mechanisms	—	Invasive species dispersion is facilitated in roadside areas
Structural state	Vegetation form & stratification	Management strategies and roadside microhabitats influence plant classes		Herbaceous species are dominant closer to the road Woody species are more present closer to the adjacent landscapes' edges

Figure 7.

Synthesis of main variables associated with ECT classes and their general tendencies for the flora compartment.

Roadside margins often support relatively high species richness, encompassing both regional species and those adapted to roadside conditions (Rotholz and Mandelik 2013, Arenas et al. 2017). Several studies have reported higher plant species richness along roadsides than in adjacent agricultural areas (Watkins et al. 2003, Hovd and Skogen 2005, Arenas et al. 2017). Roadside vegetation exhibits significant variation in abundance, richness and diversity, influenced by a combination of environmental (Hovd and Skogen 2005, Pourrezaei et al. 2020, Guzmán et al. 2022) and anthropogenic factors (Karim and Mallik 2008, Bernes et al. 2017, Jakobsson et al. 2018). These areas act as important habitats for nature-value species, including those with protected status (Arenas et al. 2017) and meadow and grassland species whose natural habitats have become increasingly scarce. However, proximity to roads may negatively affect native plant populations, while favouring invasive alien species, which tend to be more

abundant near the road and less frequently established in adjacent ecosystems (Watkins et al. 2003, Neher et al. 2017, Motti et al. 2021).

Regarding plant functional strategies, high soil nitrogen content and disturbance levels near the road edge favour nutrient-demanding and ruderal species (Hovd and Skogen 2005, Truscott et al. 2005, Arenas et al. 2017), whereas competitive species tend to become more abundant with increasing distance from the road (Truscott et al. 2005). Road infrastructure and traffic pollution impact roadside vegetation by causing alterations in several leaf traits; this causes an overall reduction in their photosynthetic activity (Shahrukh et al. 2023, Mehmood et al. 2024). The reviewed literature also indicates that road verges facilitate plant dispersal, including both invasive alien species (Gelbard and Belnap 2003, Joly et al. 2011) and grassland species (Tikka et al. 2001). Traffic intensity (Lemke et al. 2019) roadside maintenance activities, particularly mowing machinery (Chaudron and Isselin-Nondedeu 2017), can influence seed dispersal distance along roadsides.

Finally, vegetation form and stratification are shaped by roadside microtopography and maintenance practices. Roadside vegetation includes herbaceous plants, such as grasses and forbs and woody species, including shrubs and trees (Lee and Power 2013, Depalma and Mermoz 2019). The dominance of different plant classes varies depending on the roadside micro-habitat and management strategies. Herbaceous vegetation generally dominates the areas closest to the road, where maintenance aims to preserve visibility and limit woody vegetation growth (Karim and Mallik 2008, Truscott et al. 2005). In contrast, shrub abundance tends to be higher on back slopes than in other roadside sections (Karim and Mallik 2008, Neher et al. 2013, Neher et al. 2017, Watkins et al. 2003).

Roadside fauna compartment

A synthesis of the key variables for the fauna is presented in Fig. 8. Roadside fauna comprises a diverse range of invertebrate and vertebrate species, with community composition often differing from that of surrounding habitats (Rotholz and Mandelik 2013, Ruiz-Capillas et al. 2013, Morelli et al. 2014). For example, wild bees benefitted from linear ecosystems, as these sites provided nesting and foraging opportunities, leading to higher abundance and species richness compared, for example, to urban forest areas (Twerd et al. 2021). However, proximity to roads also exposes fauna to vehicle collisions, with mortality risk influenced by road width, traffic volume, vegetation abundance and structure and species behaviour (Delgado et al. 2007, Secco et al. 2022). Similarly to flora, roadsides can provide habitats for species of conservation concern, including certain pollinators, other insects and birds; acting as remnant ecosystems of their native habitats (Amatta et al. 2023, Andersson et al. 2017, Depalma and Mermoz 2019). However, roadside disturbances may also favour alien and invasive species, as reported for honeybees (Apis mellifera) in Argentina (Monasterolo et al. 2020), the brown marmorated stink bug (*Halyomorpha halys*) in the United States (Gardiner et al. 2018) and the isopod (Armadillidium vulgare) in Hungary (Vona-Túri 2019).

ECT class	Variable	Tendency	Specifications
Compositional state	Fauna abundance, richness, and diversity	Differs from fauna in the surrounding environments	They host a wide range of invertebrates and vertebrates
"	Species status (nature value, alien & invasive alien species	Host species with conservation status Alien and invasive species thrive due to disturbance	Pollinators and endangered birds have been reported in roadside areas
Functional state	Nesting	Grassland bird species and pollinators use roadsides as nesting sites	Microtopographic elements provide different microhabitats that host different species
"	Food source	Provide foraging for a wide range of organisms	Flowering resources benefit pollinators Omnivorous birds benefit from these areas
"	Movement	Roadsides function as corridors or barriers	Influenced by species characteristics and their habitat requirements, as well as road characteristics, and landscape
Structural state	Distribution	Can function as refuges for species in highly anthropized environments	Roadside management can influence their carrying capacity

Figure 8.

Synthesis of main variables associated with ECT classes and their general tendencies for the fauna compartment.

Roadsides provide nesting and foraging opportunities for various fauna groups. The different microhabitats, such as bare ground and herbaceous vegetation, provide nesting and breeding sites for a range of species such as bees (Twerd et al. 2021) and birds (Safratowich et al. 2008, Gardiner et al. 2018, Depalma and Mermoz 2019). However, breeding near roads may increase the risk of vehicle collisions involving young birds (Depalma and Mermoz 2019). By supporting vegetation, therefore, containing plant leaves, litter and flowers, as well as other food sources, roadsides provide foraging opportunities for a wide range of organisms such as decomposers (Vona-Túri et al. 2017, Vona-Túri 2019), birds (Morelli et al. 2014, Kroeger et al. 2022) and pollinators (Andersson et al. 2017, Gardiner et al. 2018, Monasterolo et al. 2020).

Roadsides can also function as movement corridors, whereas roads themselves may act as barriers, depending on species mobility and habitat requirements (Ji et al. 2017). Roadside ditches have been reported to facilitate the movement of amphibians and reptiles (Homyack et al. 2016), as well as the ant*P. occidentalis* (DeMers 1993). Conversely, reduced movement across roads has been documented for small flying insects, including pollinators (Andersson et al. 2017) and amphibians such as frogs and toads (Gravel et al. 2012).

Finally, the distribution of roadside fauna varies with the degree of landscape modification. In relatively undisturbed environments, roadsides may support lower species abundance or richness than adjacent natural habitats, as reported in Amazonian forests (Maynard et al. 2016) and African tropical ecosystems (Laurance et al. 2008). In contrast, roadsides in highly modified landscapes can provide refuges for small

mammals, as observed in central Spain (Ruiz-Capillas et al. 2013). Roadside management practices may further influence habitat suitability and carrying capacity for small mammals (Galantinho et al. 2017, Galantinho et al. 2020).

Interactions based on their ecological relevance

The compartment-by-compartment analysis presented in the following sections reveals that roadside ecosystems cannot be adequately understood through the lens of any single compartment in isolation. Across all five compartments, variables consistently respond to the same anthropogenic pressures, follow overlapping spatial gradients and influence one another through feedback mechanisms that cut across compartment boundaries. These cross-compartment interactions are structurally embedded in roadside functioning. The following subsections synthesise the most ecologically significant of these interactions, organised around the processes through which they operate: biogeochemical cycling, pollutant transfer, hydrological dynamics, microtopographic control, flora-fauna linkages and anthropogenic pressure pathways.

Biogeochemical Cycles: Linking Soil, Water, Vegetation and Atmospheric Processes

The interplay between soil nutrients (carbon, nitrogen and potassium), soil moisture, water pollutants, atmospheric compounds (GHG, NOx, NH_3) and vegetation define the core biogeochemical dynamics of roadside environments.

Roadside ditches alter runoff and flow patterns, often leading to reduced soil moisture (Buchanan et al. 2013). Soil moisture acts as a key regulatory variable, controlling water availability for vegetation. For instance, Lee and Power (2013) found that higher soil moisture was positively correlated with grass cover and species richness in calcareous roadsides in the United Kingdom, while Karim and Mallik (2008) identified soil moisture as a dominant factor determining roadside plant community composition in Canada. In line with this, Hovd and Skogen (2005) explained that tall and dense vegetation cover increased soil moisture levels by increasing litter and reducing light penetration.

Studies have highlighted the key role of vegetation, particularly in vegetated roadside ditches, as hotspots for nitrogen removal through microbial processes (McPhillips et al. 2016, Tatariw et al. 2021). Vegetation and water interact closely during denitrification (reduction of nitrogen content in water), as root systems enhance microbial activity, facilitating nitrogen removal from water and improving water quality (Tatariw et al. 2021). However, grassed ditches act both as nitrogen sinks and as GHG sources, highlighting the dual nature of biogeochemical feedbacks. McPhillips et al. (2016) showed that methane emissions increased with soil moisture, whereas nitrous oxide emissions decreased with soil moisture, but increased with soil nitrates (soil nitrogen nutrients). Similarly, carbon dioxide emissions from soil respiration were positively correlated with carbon and nitrogen content in soil, but negatively influenced by soil moisture. This illustrates tight reciprocal linkages amongst nutrient cycling, microbial processes, soil

nutrient content and hydrology, connecting abiotic conditions to biological activity across multiple compartments simultaneously.

Pollutant Deposition and Ecosystem Feedback

Pollutant transfer across compartments occurs through several interconnected pathways, depending on the source of pollution. Airborne contaminants such as heavy metals, particulate matter, nitrogen oxides, ammoniac emissions and PAH are deposited on to soil, water and vegetation (Aslan et al. 2011, Brantley et al. 2014, Tatariw et al. 2021), forming a diffuse contamination network (Wawer et al. 2015, Nikolaeva et al. 2021).

Vegetation plays a dual regulatory role in these exchanges (Baldauf 2017), by acting as a biological filter, capturing airborne particulate matter and reducing local exposure levels. For example, Abhijith and Kumar (2020) demonstrated that traffic-facing foliage of roadside hedges retained significantly more PM than the leeward side, reducing downwind dispersion. Similarly, Brantley et al. (2014) observed that maple and oak trees effectively reduced black carbon and coarse PM (PM_{2}–PM_{10}) under favourable wind conditions, although finer particles ($PM_{0.5}$–PM_{2}) were less affected.

However, the interaction between pollutants and vegetation extends beyond filtration. Vegetation can bioaccumulate pollutants, such as heavy metals and PAHs, with peak concentrations typically occurring near the road and declining with distance towards background levels (Amrhein et al. 1992, Nikolaeva et al. 2021). Soil characteristics modulate these transfers: i.e. high salt concentrations increase heavy metal mobility, whereas organic matter and clay particles (soil texture) can immobilise them by binding ions and reducing their bioavailability (Amrhein et al. 1992, Modlingerová et al. 2012).

Air pollutants also have direct physiological effects on plants, altering their growth and development. In controlled experiments, Honour et al. (2009) showed that exposure to particulate matter and nitrogen oxides led to reduced plant height, delayed flowering and accelerated leaf senescence. Similarly, field studies demonstrated that traffic-related air pollution modifies stomatal behaviour, reducing chlorophyll content and lowering photosynthetic efficiency in roadside vegetation (Shahrukh et al. 2023, Mehmood et al. 2024). These pollutant pathways illustrate how traffic, as a primary anthropogenic pressure, propagates through air, soil, water and flora, resulting in cascading effects that single-compartment analysis could not capture.

Hydrological Processes and Pollutant Transport

Rainfall and stormwater runoff play a critical role in pollutant transportation and re-distribution in roadside environments. The “first flush effect” describes the rapid mobilisation of pollutants accumulated in soils during dry periods, with initial runoff carrying disproportionately high pollutant loads in water (Kayhanian et al. (2012), Lerat-Hardy et al. (2022)). This phenomenon affects heavy metals, nitrogen,and phosphorus, which are disproportionately released in the early stages of runoff events (Lerat-Hardy et al. 2022).

Soil hydrology further governs pollutant fate. For instance, lead (Pb) and zinc (Zn) tend to accumulate in subsoil layers through leaching and infiltration, with movement intensity depending on runoff concentrations, soil type (which includes variables such as soil texture and soil OM) and initial surface concentration of pollutants (Zhao and Hazelton 2016). These processes demonstrate the tight coupling between rainfall patterns that produce runoff, soil properties and contaminant mobility, where water acts as a transport vector linking compartments and making hydrological dynamics a structurally important axis of roadside ecosystem functioning.

Influences of microtopography and soil-flora feedbacks

Microtopography — comprising shoulders, slopes, ditches and back slopes — creates fine-scale variations in soil conditions that strongly influence vegetation, reflecting differences in moisture, compaction and nutrient availability (Karim and Mallik 2008).

Soil properties, such as pH, salinity, bulk density, nutrient content and texture, differ between microtopographic elements, directly influencing plant establishment and growth (Jimenez et al. 2013, Neher et al. 2013, Mills et al. 2021, Guzmán et al. 2022) and, thus, species richness and abundance (Karim and Mallik 2008, Mills et al. 2021). For example, compaction on shoulders, caused by traffic of vehicles and maintenance equipment, limits root development and tree recruitment (McGrath and Henry 2015).

Conversely, vegetation also modifies soil properties over time. As roadsides age, plant succession can enhance soil fertility by increasing soil nutrient content and organic matter (García-Palacios et al. 2011, Jimenez et al. 2013). This bidirectional relationship between soil and flora exemplifies the feedback dynamics that characterise roadside as ecosystems, rather than as mere assemblages of independent components.

Influences of microtopography and flora-fauna interactions

Microtopographic features also shape faunal distribution and habitat use. Ditches and slopes create specific ecological niches for wetland plant species, which influence plant community composition in the roadside. Favouring wetland-adapted plants also favours wetland-adapted fauna, influencing fauna abundance, richness and diversity in these areas (Safratowich et al. 2008, Homyack et al. 2014, Neher et al. 2017). For example, the height and density of wetland plant Cattail (*Typha latifolia*) were positively correlated with wetland bird species density (e.g. *Xanthocephalus xanthocephalus*, *Cistothorus palustris* and *Charadrius vociferus*) in U.S. roadsides (Safratowich et al. 2008). Another example of the strong interactions between flora and fauna is shown in a study carried out in Argentina, where ground-nesting birds exhibited higher population densities in areas with tall grass cover, which provides nesting shelter and protection from predators, while tree presence was negatively associated with nesting success (Depalma and Mermoz 2019). In invertebrates, ditch orientation and soil texture also play a role, as observed for south-facing slopes with sandy soils that favour the installation of ant mounds, shaping this species distribution (DeMers 1993). These examples illustrate how microtopographic heterogeneity acts as a structural driver that propagates through soil and flora conditions

before ultimately shaping faunal communities, linking the physical configuration of roadsides to their biological diversity.

Pressures influencing roadside ecosystems

In addition to interactions amongst ecosystem variables, roadside ecosystems are shaped by a range of anthropogenic and environmental pressures. To examine how these drivers are addressed in literature, pressure–variable relationships were synthesised across five major pressure categories: traffic; surrounding landscape; microtopography (roadside sections such as shoulder, berm and ditch); roadside maintenance practices (e.g. mowing frequency, ditch clearing); and road and roadside presence. This latter category encompasses disturbances associated with road construction and long-term existence, as well as structural road characteristics, including age, type and spatial extent.

The frequency of reported pressure–variable relationships is shown in Fig. 9. These frequencies indicate how often specific pressures are addressed in relation to ecosystem variables in literature and should be interpreted as a measure of research emphasis rather than intrinsic ecological importance or impact magnitude. Microtopography, road and roadside presence are the most frequently documented pressures, followed by traffic and landscape context, whereas roadside maintenance is comparatively less represented.

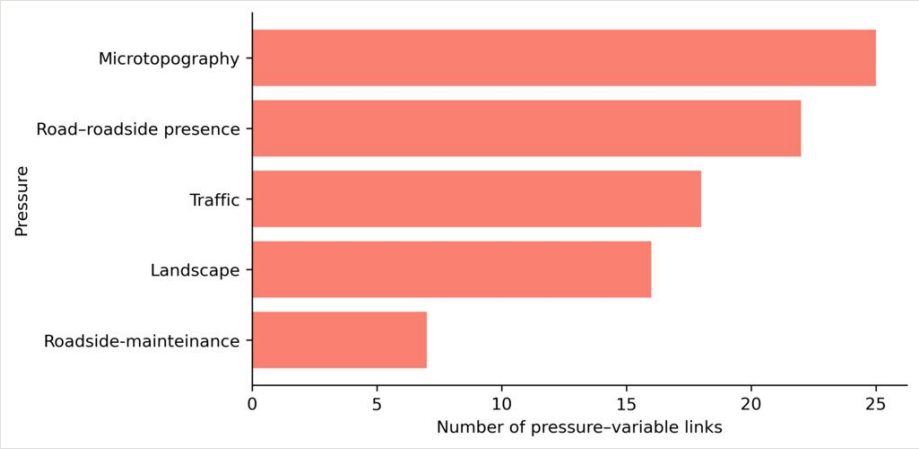


Figure 9.

Frequency of documented pressure–variable relationships across the 97 studies included in the literature review. Bars indicate the number of documented links between each pressure category and ecosystem variables in the reviewed articles. Microtopography refers to roadside sections (e.g. shoulder, ditch and slope). Road_roadside refers to the presence of these elements and their consequences related to the road characteristics. Traffic encompasses the pressures related to vehicle circulation. Landscape refers to the influences which the sourrounding areas apply in the roadside variables. Roadside maintenance refers to the actions, such as mowing and clearing, that are carried out in roadside areas.

A more detailed view of how pressures influence variables is presented in Fig. 10. Traffic-related pressures are predominantly linked to air-quality variables, but also extend to soil and vegetation attributes. In contrast, microtopography and road–roadside configuration exhibit broader interaction patterns, affecting variables across multiple compartments, including flora, soil, fauna and water variables. Roadside maintenance shows more limited and compartment-specific associations, primarily within vegetation-related variables. These patterns indicate that pressures influence roadside ecosystems in differentiated ways and that research attention varies substantially amongst pressure types.

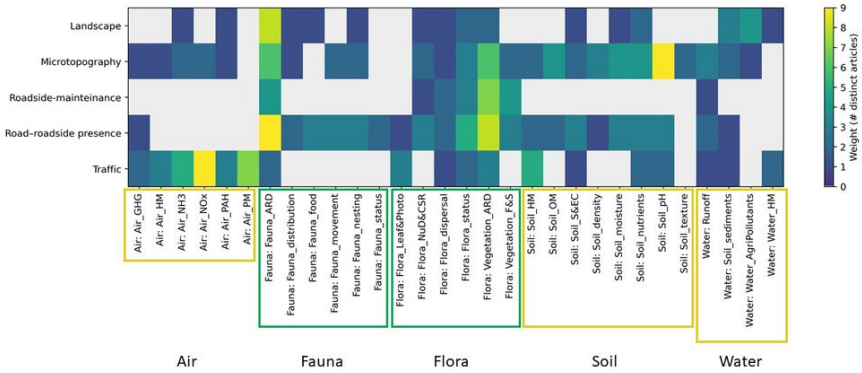


Figure 10.

Pressure-variable relationship heatmap. Shows the frequency of the reported influences over the different variables. Grey cells indicate no influences are reported. Variables are grouped by compartments, the abiotic compartments (air, soil and water) in yellow frames. In green frames, the biotic compartments (flora and fauna).

Beyond these descriptive patterns, Fig. 10 highlights several structuring features in the representation of pressures across ecosystem compartments. Variables related to soil properties (e.g. soil moisture, soil chemistry) and vegetation structure emerge as key intermediary nodes, linking multiple pressure categories to both biotic and abiotic responses. Microtopography and road–roadside configuration exhibit the widest range of connections, underscoring their central role in shaping roadside ecosystem functioning. By contrast, roadside maintenance practices appear comparatively under-represented, revealing a potential knowledge gap despite their recognised influence on vegetation structure and associated ecological processes. Taken together, the pressure-variable relationships documented across compartments confirm that roadside ecosystems respond to anthropogenic drivers not as isolated components, but as integrated systems, where interventions in one compartment routinely generate responses across others.

This finding has direct implications for how roadside management should be conceived and evaluated.

Discussion

Interpretation of pressure-response pathways

To explore this integrative dimension, a pathway-based synthesis was developed by combining pressure–variable and variable–variable interactions and aggregating them at the compartment level. Rather than inferring causal relationships, this visualisation supports a conceptual understanding of how anthropogenic pressures may propagate through roadside ecosystems. Fig. 11 highlights the central role of flora and soil as intermediate compartments receiving multiple pressures before transferring effects to other system components. Flora is influenced by all five pressure categories considered and shows strong connections with fauna, reflecting the role of vegetation in providing habitat structure and food resources. Soil also emerges as a highly interconnected compartment, characterised by numerous interactions both within and across compartments, consistent with its role in regulating physical, chemical and biological processes. Finally, the presence of within-compartment loops emphasises internal feedback amongst variables, reinforcing the systemic nature of roadside ecosystems. Overall, this pathway-based representation provides a pressure–response perspective that complements the compartment-based analyses by situating individual interactions within a broader system-level framework.

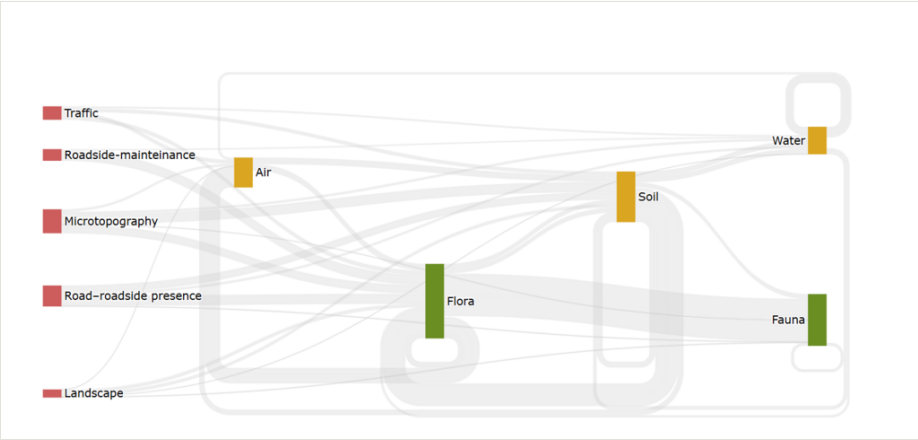


Figure 11.

Sankey diagram showing the pathways from pressures to roadside compartments and interactions amongst them. Pathway support is represented by link width and is defined as the minimum frequency of the two constituent interactions across distinct scientific articles. Node colours indicate node type and biophysical compartment, distinguishing pressures (in red) from abiotic compartments air, soil, water (in yellow) and biotic compartments flora and fauna (in green).

Traffic-related pollution, routine road maintenance activities such as salting and roadside configuration and maintenance emerge as major drivers influencing soil chemistry, vegetation structure and faunal communities (Gunawardena et al. 2012, Neher et al. 2013, Brantley et al. 2014, Zhu et al. 2022). For instance, de-icing techniques increase soil pH and salt content (Truscott et al. 2005, Willmert et al. 2018), while mechanical mowing modifies vegetation structure and indirectly affects pollinator and bird communities (Abhijith and Kumar 2020, Nikolaeva et al. 2021, Tatariw et al. 2021, Shahrukh et al. 2023). These pressure–variable relationships form cascading pathways across compartments, consistent with the multi-step connections, illustrated in Fig. 11.

Roadside configuration and microtopography further modulate these pathways by shaping local environmental conditions. Variations amongst shoulders, berms, ditches and slopes are associated with distinct soil and vegetation properties, reflecting both their functional roles within road infrastructure and differences in management interventions. Several studies have shown that the properties of soil and vegetation differ amongst microtopographic elements because they fulfil different infrastructure functions and are consequently subject to different types of maintenance intervention. For example, Marche et al. (2022) showed that mowing height, timing and frequency affect vegetation cover and the spread of invasive species. Within the proposed framework, these effects translate into changes in the flora compartment variables, including abundance, richness, diversity, structure, stratification and species status, as well as indirect influences on soil properties, such as bulk density, soil moisture and organic matter.

Taken together, these interacting pressures, configurations and landscape effects explain why roadside ecosystems differ from other herbaceous-dominated systems. Their linear geometry, proximity to traffic, exposure to recurrent disturbance from maintenance and configuration from heterogeneous microtopographic units generate specific pressure–response pathways that differentiate roadside ecosystems from semi-natural grasslands or field margins (e.g. Hovd and Skogen (2005), Karim and Mallik (2008)). Being areas that are intensively managed for road user safety, which imposes regular mowing, vegetation control and drainage maintenance, highlights the relevance of management strategies (Marche et al. 2022) for looking at these areas with an ecological approach that can promote ecosystem services (Phillips et al. 2020a, Phillips et al. 2020b).

Roadsides, gradient-based ecosystems

Across all compartments, a consistent pattern emerging from the reviewed studies is the presence of environmental gradients extending from the road edge towards adjacent ecosystems. These gradients reflect decreasing intensity of anthropogenic pressures — such as traffic emissions, soil compaction, salting and maintenance disturbance — and are expressed through progressive changes in air quality, soil properties, vegetation structure and species composition. Conceptualising roadsides as gradient-based socio-ecosystems provides a unifying framework to interpret these spatial patterns and their associated feedbacks, linking local biophysical responses to broader infrastructure-driven processes.

At a broader scale, roadsides represent one of the largest continuous anthropogenic ecosystems globally, stretching over millions of kilometres across diverse biogeographic contexts. Although local conditions, such as climate, soil type and land use, strongly influence specific variable values, consistent special gradients emerge across contexts. For example, in soils, pollutant concentrations (e.g. heavy metals, salts) and physical alterations (pH, bulk density, texture) decline gradually with distance from the road, converging towards background conditions (Neher et al. 2013, Mills et al. 2021).

Similarly, in the air compartment, pollutant concentrations (PM, NO_x, NH_3, PAHs) decrease with distance from the road, although background values may be reached only at several hundred metres due to atmospheric mixing and wind turbulence (Nikolaeva et al. 2021).

These abiotic gradients directly shape vegetation structure and community composition. Areas close to the road are dominated by low-height, disturbance-tolerant herbaceous species, while shrubs and trees increase progressively further away, forming a vertical and compositional gradient (Hovd and Skogen 2005, Karim and Mallik 2008). At the same time, vegetation influences nutrient cycling, air quality, soil stability and fertility and water quality (McGrath and Henry 2015, McPhillips et al. 2016, Abhijith and Kumar 2020). For example, the presence of vegetation on roadside ditches alters hydrological flow paths, contributing to pollutant retention and removal through denitrification and microbial processing (Tatariw et al. 2021). Feedback loops between soil moisture and vegetation regulate nutrient availability and plant diversity, influencing ecosystem functioning (Karim and Mallik 2008, García-Palacios et al. 2011).

Roadside's relevance for biodiversity

The flora-fauna linkage is another key element of roadside dynamics. Vegetation provides habitat, food resources and nesting sites for numerous taxa, including pollinators, soil invertebrates, birds and small mammals (Safratowich et al. 2008, Depalma and Mermoz 2019, Twerd et al. 2021). Structural heterogeneity and floral diversity can be associated with high insect abundance and diversity, which, in turn, can support species at higher trophic levels, such as birds and small mammals.

Roadsides often exhibit higher species richness than neighbouring habitats (Ruiz-Capillas et al. 2013, Morelli et al. 2014, Arenas et al. 2017). In addition, due to their linear shape, roadsides can represent a favourable corridor for some plant and animal species. Both vegetation and fauna compartments support species of conservation interest, but also invasive species, due to the relatively high level of disturbances. This highlights the importance of considering management practices to reinforce the role of road verges for biodiversity conservation and ecosystem services provision, while limiting the spread of invasive species, which can provide disservices to society.

Variable's implementation and management perspective

The variables and interactions identified through this literature review highlight the interconnected nature of roadside ecosystems and raise the question of how they can be practically mobilized for monitoring and management purposes. The concept of essential variables as a minimum set of measurements that balance feasibility and relevance, sitting between raw field observations and higher-level indicators, has been proposed as a way to prioritise biodiversity monitoring efforts at broad scales (Pereira et al. 2013). Similarly, Niemeijer and de Groot (2008) argued that indicator selection should be grounded in the systemic inter-relations amongst variables rather than in the individual properties of each indicator evaluated in isolation. Building on these principles, this study proposes a preliminary prioritisation of 10 amongst the 30 identified variables to support roadside ecosystem condition assessment under the SEEA-EA framework.

The prioritisation followed two complementary steps. First, a literature-based composite index was developed using three criteria: (i) the frequency of reported interactions between biophysical variables, considering each variable as either a source or target; (ii) the frequency of reported associations between variables and roadside pressures; and (iii) the number of distinct articles documenting each variable, regardless of its position in the reported interactions. These criteria were normalised and combined using different weighting scenarios to the three defined criteria (Suppl. material 3). The resulting index provided an initial quantitative basis for prioritisation rather than a definitive selection criterion.

In a second step, the selection was refined according to the principles of the United Nations et al (2021) SEEA-EA framework and the criteria proposed by Czúcz et al. (2021b). Preference was given to variables describing stocks rather than associated flows and to those sensitive to human pressures. The selection also sought to ensure complementarity across ecological characteristics, retaining at least one variable within each of the five ECT state classes considered in this study. The final core set, therefore, combined literature-based prioritisation with ecological relevance and representation across ECT classes. This approach resulted in the identification of the reduced set of variables presented in Fig. 12.

Within the physical state, soil moisture and bulk density were retained as complementary variables; they reflect the direct influence of road infrastructure on soil properties, but also impact coming from hydrological dynamics, as well as physical constraints on vegetation establishment (Buchanan et al. 2013, McGrath and Henry 2015). For the chemical state, soil nutrients, heavy metals in soil and organic matter were selected to characterise complementary aspects of roadside soil conditions. Nutrient availability and organic matter contribute to soil quality and vegetation establishment, whereas heavy metal concentrations reflect pollution associated with traffic emissions and vehicle component wear. The three variables exhibit clear spatial gradients associated with road-related pressures, providing information on soil chemical conditions and their alteration across roadside areas (Johnston and Johnston 2004, Mills et al. 2021, Nikolaeva et al. 2021).

The compositional state is represented by vegetation and fauna abundance, richness and diversity, together with vegetation species status. These variables characterise roadside biological communities, while distinguishing their diversity and abundance from their conservation value and the presence of invasive alien species (Rotholz and Mandelik 2013, Arenas et al. 2017, Motti et al. 2021). Within the functional state, fauna nesting sites were retained to represent the potential of roadside habitats to support breeding activities, reflecting the ecological opportunities provided by different roadside microhabitats (Depalma and Mermoz 2019, Twerd et al. 2021). Finally, vegetation form and stratification were selected for the structural state, reflecting vegetation organisation and its response to microtopography and management. Beyond habitat provision, vegetation structure can influence atmospheric pollutant dispersion, such as particulate matter retention (Brantley et al. 2014, Baldauf 2017).

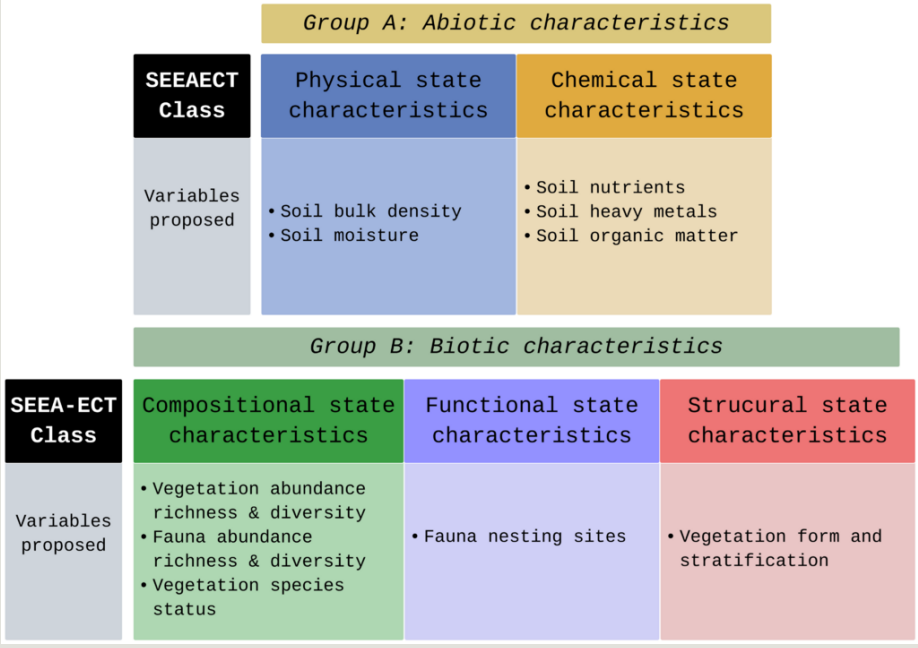


Figure 12.

Proposed core set of biophysical variables for roadside ecosystem condition assessment, organised by SEEA-EA Ecosystem Condition Typology (ECT) classes.

The reviewed literature consistently identifies pollution gradients as characteristic features of roadside ecosystems, particularly in the air and soil compartments. Accordingly, soil heavy metals were retained to reflect these conditions. However, other variables, such as salt content and electrical conductivity, characteristic of roadsides in temperate regions, were not retained in this initial selection; their relevance is particularly associated with winter road de-icing practices (Willmert et al. 2018). Therefore, the proposed selection should be adapted to the specific context and intended application,

considering on local pressures, environmental conditions and the objectives of the assessment.

The proposed core set provides a preliminary basis for roadside ecosystem condition monitoring rather than a validated assessment framework. Its selection reflects the representation of variables and their documented interactions in the reviewed literature, complemented by considerations of ecological relevance and coverage of ECT classes. Furthermore, measurement feasibility, monitoring costs and the sensitivity and reliability of the selected variables have not been systematically evaluated. Future field-based studies across contrasting roadside and management contexts are, therefore, needed to validate the proposed selection, establish suitable measurement protocols and reference conditions and assess its applicability within the SEEA-EA framework.

Conclusion and perspectives

This study proposes a systemic framework for characterising roadside ecosystems using a compartment-based approach aligned with the SEEA Ecosystem Condition Typology (ECT). Based on a review of 97 articles, 30 key variables were identified and organised into five compartments — air, soil, water, flora and fauna — crossed with SEEA biophysical state classes. The synthesis revealed that flora is the compartment most strongly influenced by anthropogenic pressures and exhibits strong interactions with fauna, while soil emerged as the most connected compartment, influencing all others. Together, these results highlight the central role of flora and soil in roadside ecosystem functioning and confirm that roadsides operate as gradient-based systems, organised along spatial transitions driven by decreasing pressure intensity from the road edge towards surrounding ecosystems.

Although many of the biophysical variables identified in this study are common to other terrestrial ecosystems, their expression in roadside environments is shaped by two distinctive characteristics: exposure to traffic-related and maintenance pressures and pronounced microtopographic heterogeneity. First, their immediate proximity to traffic and road maintenance activities generates pollution inputs, including traffic-related contaminants and de-icing salts, producing marked spatial gradients, particularly across air and soil compartments. Second, their structural configuration creates pronounced microtopographic zonation, particularly affecting soil and vegetation characteristics, which, in turn, influence water, air and fauna dynamics. These characteristics highlight the importance of accounting for roadside-specific pressures when selecting variables for ecosystem condition assessment. Building on these findings, this study proposes a core set of 10 biophysical variables across the five ECT state classes as an initial basis for roadside ecosystem condition assessment. This selection remains adaptable to local conditions and assessment objectives and requires further empirical validation.

Despite growing ecological challenges, including biodiversity loss, climate change and increasing pressure on natural resources, roadside management practices remain largely driven by safety and operational requirements. Yet roadsides offer significant

opportunities for ecological optimisation. The proposed framework and core set of variables provide a starting point for systematic condition assessment and more ecologically informed management. This may support the identification of potential trade-offs between ecosystem services and disservices, contributing to the development of more adaptive and ecologically informed roadside management strategies.

From a management perspective, the gradient structure of roadsides provides a spatial basis for differentiating interventions by zone. Areas in proximity to the road are subject to the highest-pressure intensities and are typically managed primarily for road user safety. As distance from the road increases, management intensity can be progressively reduced, allowing flora richness, structural complexity and vertical stratification to develop. These conditions, in turn, provide resources for fauna compartments, reinforcing the potential of roadsides to function as corridors and refuges for flora and fauna conservation, provided that invasive species spread is actively monitored and controlled. Such zonation-based management is particularly relevant in the context of sustainable infrastructure planning, green networks and biodiversity offset policies, where roadsides can serve as multifunctional ecological assets.

The results should be interpreted as indicative gradients rather than universal benchmarks. Roadside functioning is strongly influenced by local factors, such as road design, surrounding land use and landscape context and future studies integrating spatially explicit approaches and contrasting environmental conditions are needed to strengthen the framework's applicability. The SEEA-ECT framework applied here provides a transferable and internationally recognised structure for this purpose, offering a foundation for the development of standardised roadside ecosystem condition accounts that can provide information for both research and infrastructure management policy.

Declaration of generative AI and AI-assisted technologies in the writing process

In line with One Ecosystem’s policy, we disclose the following uses of AI tools. Data handling and analysis: ChatGPT and Claude (Anthropic) were used to write code that cleaned the extraction dataset, used to produce and improve Python figure code and to rank candidate core variables (Supplementary Material 3). All inputs, judgement criteria and final decisions on variable selection were set by the authors. Text refinement: ChatGPT was used to improve the language of the text previously written by the authors. No AI tool was used to write the text, to generate data or results or to select references without verification. All AI-assisted content was reviewed and verified by the authors, who take full responsibility for the manuscript.

Acknowledgements

This work was carried out in the context of the SAGID+ project, which is co-funded by the European Union with the European Regional Development Fund to the tune of €409 500,

by the ACTIBAC group and the Métropole du Grand Nancy. It contributes to the collective ambition “Des Hommes et Des Arbres, les racines de demain” (People and Trees, the roots of tomorrow), labelled as an Innovation Territory.

Funding program

SAGID+ project

Author contributions

Z.M.S. B.M. and C.C and contributed to the ideas, the methodology and the interpretation of the results. They also led the writing of the manuscript. M.C.P. contributed to the writing of the manuscript and the interpretation of the results.

Conflicts of interest

The authors have declared that no competing interests exist.

References

- Abhijith KV, Kumar P (2020) Quantifying particulate matter reduction and their deposition on the leaves of green infrastructure. Environmental Pollution 265 https://doi.org/10.1016/j.envpol.2020.114884
- Amatta E, Andino N, Calcaterra LA, Giannoni SM (2023) Effect of road disturbance on ant diversity in the Monte desert of Argentina. Journal of Insect Conservation 27 (4): 533-545. https://doi.org/10.1007/s10841-023-00477-9
- Amrhein C, Strong J, Mosher P (1992) Effect of deicing salts on metal and organic matter mobilization in roadside soils. Environmental Science & Technology 26 (4): 703-709. https://doi.org/10.1021/es00028a006
- Andersson P, Koffman A, Sjödin NE, Johansson V (2017) Roads may act as barriers to flying insects: species composition of bees and wasps differs on two sides of a large highway. Nature Conservation 18: 47-59. https://doi.org/10.3897/natureconservation.18.12314
- Arenas J, Escudero A, Mola I, Casado M (2017) Roadsides: an opportunity for biodiversity conservation. Applied Vegetation Science 20 (4): 527-537. https://doi.org/10.1111/avsc.12328
- Aslan A, Çiçek A, Yazici K, Karagöz Y, Turan M, Akkus F, Yildirim O (2011) The assessment of lichens as bioindicator of heavy metal pollution from motor vehicles activites. African Journal of Agricultural Research 6: 1698-1706. https://doi.org/10.5897/AJAR10.331
- Baldauf R (2017) Roadside vegetation design characteristics that can improve local, near-road air quality. Transportation Research Part D: Transport and Environment 52: 354-361. https://doi.org/10.1016/j.trd.2017.03.013

- Bernes C, Bullock J, Jakobsson S, Rundlöf M, Verheyen K, Lindborg R (2017) How are biodiversity and dispersal of species affected by the management of roadsides? A systematic map. Environmental Evidence 6 (1). https://doi.org/10.1186/s13750-017-0103-1
- Beschta R (1978) Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14 (6): 1011-1016. https://doi.org/10.1029/WR014i006p01011
- Bilby R, Sullivan K, Duncan S (1989) The Generation and Fate of Road-Surface Sediment in Forested Watersheds in Southwestern Washington. Forest Science 35 (2): 453-468. https://doi.org/10.1093/forestscience/35.2.453
- Blakey MC, Bonasso SG, Brewster RM, Bugliarello G, Collins TH, Dorn JL, Eberhardt JJ, Hamberger ER, Horsley JC, Jamison RD, Johnson E, Kowalewski R, Millar WW, Peters ME, Rudzinski S, Runge JW, Sandberg AM, Schubert WG, Shane JN, Strock CA, Gen M, Army US (2005) Integrated Roadside Vegetation Management. NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM7-19.
- Brantley H, Hagler GW, J. Deshmukh P, Baldauf R (2014) Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. Science of The Total Environment 468-469: 120-129. https://doi.org/10.1016/j.scitotenv.2013.08.001
- Buchanan B, Easton Z, Schneider R, Walter MT (2013) Modeling the hydrologic effects of roadside ditch networks on receiving waters. Journal of Hydrology 486: 293-305. https://doi.org/10.1016/j.jhydrol.2013.01.040
- Buchanan BP, Falbo K, Schneider RL, Easton ZM, Walter MT (2013) Hydrological impact of roadside ditches in an agricultural watershed in Central New York: implications for non-point source pollutant transport. Hydrological Processes 27 (17): 2422-2437. https://doi.org/10.1002/hyp.9305
- Budai P, Clement A (2018) Spatial distribution patterns of four traffic-emitted heavy metals in urban road dust and the resuspension of brake-emitted particles: Findings of a field study. Transportation Research Part D: Transport and Environment 62: 179-185. https://doi.org/10.1016/j.trd.2018.02.014
- Campos P, Mesa B, Álvarez A, Oviedo J, Caparrós A (2022) Towards measuring environmental income through a refined United Nations SEEA EA: Application to publicly-owned, protected, pine-forest-farm case studies in Andalusia, Spain. Ecological Economics 201 https://doi.org/10.1016/j.ecolecon.2022.107570
- Cape JN, Tang YS, van Dijk N, Love L, Sutton MA, Palmer SCF (2004) Concentrations of ammonia and nitrogen dioxide at roadside verges, and their contribution to nitrogen deposition. Environmental Pollution 132 (3): 469-478. https://doi.org/10.1016/j.envpol.2004.05.009
- Chapin FS, Matson P, Vitousek P (2011) Principles of Terrestrial Ecosystem Ecology. Springer New York, New York, NY, 529 pp. URL: http://link.springer.com/10.1007/978-1-4419-9504-9
- Chatain M, Chretien E, Crunaire S, Jantzem E (2022) Road Traffic and Its Influence on Urban Ammonia Concentrations (France). Atmosphere 13 (7). https://doi.org/10.3390/atmos13071032
- Chaudron C, Isselin-Nondedeu F (2017) Assessing the effects of mowing machinery on seed dispersal pattern: a test of two methods of seed tracking. Botany Letters 164 (4): 413-423. https://doi.org/10.1080/23818107.2017.1369901

- Chaudron C, Perronne R, Di Pietro F (2018) Functional response of plant assemblages to management practices in road–field boundaries. Applied Vegetation Science 21 (1): 33-44. https://doi.org/10.1111/avsc.12346
- CIA (2020) The World Factbook. URL: https://www.cia.gov/the-world-factbook/countries/world/#transportation
- Collinson W, Parker D, Bernard RF, Reilly B, Davies-Mostert H (2019) Factors influencing the spatial patterns of vertebrate roadkill in South Africa: The Greater Mapungubwe Transfrontier Conservation Area as a case study. African Journal of Ecology 57 (4): 552-564. https://doi.org/10.1111/aje.12628
- Coskun H (2019) Static ecological system analysis A holistic analysis of compartmental systems. Theoretical Ecology 13: 17-52. https://doi.org/10.1007/s12080-019-0421-8
- Czúcz B, Götzl M, Schwaiger E, Schwarzl B, Sonderegger G (2017) Working paper on functional relationships between ecosystem characteristics and services in support of condition assessments. European Topic Centre on Biological Diversity c/o Muséum national d'Histoire naturelle.
- Czúcz B, Keith H, Driver A, Jackson B, Nicholson E, Maes J (2021a) A common typology for ecosystem characteristics and ecosystem condition variables. One Ecosystem 6 https://doi.org/10.3897/oneeco.6.e58218
- Czúcz B, Keith H, Maes J, Driver A, Jackson B, Nicholson E, Kiss M, Obst C (2021b) Selection criteria for ecosystem condition indicators. Ecological Indicators 133 https://doi.org/10.1016/j.ecolind.2021.108376
- Delgado J, Arroyo N, Arévalo J, Fernández-Palacios J (2007) Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands). Landscape and Urban Planning 81 (4): 328-340. https://doi.org/10.1016/j.landurbplan.2007.01.005
- DeMers M (1993) Roadside ditches as corridors for range expansion of the western harvester ant (*Pogonomyrmex occidentalis* Cresson). Landscape Ecology 8 (2): 93-102. https://doi.org/10.1007/BF00141589
- Depalma DM, Mermoz ME (2019) Ground nesting birds in roadside borders of the Argentine Pampas: habitat use and predation risk of artificial nests. Revista Brasileira de Ornitologia 27 (4): 261-274. https://doi.org/10.1007/BF03546072
- De Silva S, Ball A, Indrapala D, Reichman S (2021) Review of the interactions between vehicular emitted potentially toxic elements, roadside soils, and associated biota. Chemosphere 263 https://doi.org/10.1016/j.chemosphere.2020.128135
- De Valck J, Jarvis D, Coggan A, Schirru E, Pert P, Graham V, Newlands M (2023) Valuing ecosystem services in complex coastal settings: An extended ecosystem accounting framework for improved decision-making. Marine Policy 155 https://doi.org/10.1016/j.marpol.2023.105761
- Domptail S, Easdale M, Yuerlita (2013) Managing Socio-Ecological Systems to Achieve Sustainability: A Study of Resilience and Robustness. Environmental Policy and Governance 23 (1): 30-45. https://doi.org/10.1002/eet.1604
- Dunnett NP, Willis AJ, Hunt R, Grime JP (1998) A 38-year study of relations between weather and vegetation dynamics in road verges near Bibury, Gloucestershire. Journal of Ecology 86 (4): 610-623. https://doi.org/10.1046/j.1365-2745.1998.00297.x
- Dvarskas A (2019) Experimental ecosystem accounting for coastal and marine areas: A pilot application of the SEEA-EEA in Long Island coastal bays. Marine Policy 100: 141-151. https://doi.org/10.1016/j.marpol.2018.11.017

- Esen SE, Hein L (2020) Development of SEEA water accounts with a hydrological model. Science of The Total Environment 737 https://doi.org/10.1016/j.scitotenv.2020.140168
- Farrell CA, Coleman L, Kelly-Quinn M, Obst C, Eigenraam M, Norton D, O'Donoghue C, Kinsella S, Delargy O, Stout J (2021) Applying the system of environmental economic accounting-ecosystem accounting (SEEA-EA) framework at catchment scale to develop ecosystem extent and condition accounts. One Ecosystem https://doi.org/10.3897/oneeco.6.e65582
- Forman RT, Alexander L (1998) ROADS AND THEIR MAJOR ECOLOGICAL EFFECTS. Annual Review of Ecology and Systematics 29 (1): 207-231. https://doi.org/10.1146/annurev.ecolsys.29.1.207
- Forman RT (2000) Estimate of the Area Affected Ecologically by the Road System in the United States. Conservation Biology 14 (1): 31-35. https://doi.org/10.1046/j.1523-1739.2000.99299.x
- Galantinho A, Eufrázio S, Silva C, Carvalho F, Alpizar-Jara R, Mira A (2017) Road effects on demographic traits of small mammal populations. European Journal of Wildlife Research 63 (1). https://doi.org/10.1007/s10344-017-1076-7
- Galantinho A, Herrera J, Eufrázio S, Silva C, Carvalho F, Alpizar-Jara R, Mira A (2020) Road verges provide connectivity for small mammals: A case study with wood mice (*Apodemus sylvaticus*) in an agro-silvo pastoral system. Journal of Environmental Management 258 https://doi.org/10.1016/j.jenvman.2019.110033
- García-Palacios P, Bowker M, Maestre F, Soliveres S, Valladares F, Papadopoulos J, Escudero
A (2011) Ecosystem development in roadside grasslands: biotic control, plant–soil interactions, and dispersal limitations. Ecological Applications 21 (7): 2806-2821. https://doi.org/10.1890/11-0204.1
- Gardiner MM, Riley CB, Bommarco R, Öckinger E (2018) Rights-of-way: a potential conservation resource. Frontiers in Ecology and the Environment 16 (3): 149-158. https://doi.org/10.1002/fee.1778
- Gelbard J, Belnap J (2003) Roads as Conduits for Exotic Plant Invasions in a Semiarid Landscape. Conservation Biology 17 (2): 420-432. https://doi.org/10.1046/j.1523-1739.2003.01408.x
- Ghosh S, Scharenbroch B, Ow LF (2016) Soil organic carbon distribution in roadside soils of Singapore. Chemosphere 165: 163-172. https://doi.org/10.1016/j.chemosphere.2016.09.028
- Grant M, Booth A (2009) A typology of reviews: an analysis of 14 review types and associated methodologies. Health Information & Libraries Journal https://doi.org/10.1111/j.1471-1842.2009.00848.x
- Gravel M, Mazerolle M, Villard M (2012) Interactive effects of roads and weather on juvenile amphibian movements. Amphibia-Reptilia 33 (1): 113-127. https://doi.org/10.1163/156853812X625512
- Grover I, O'Reilly-Wapstra J, Suitor S, Hatton MacDonald D (2023) Not seeing the accounts for the forest: A systematic literature review of ecosystem accounting for forest resource management purposes. Ecological Economics 212 https://doi.org/10.1016/j.ecolecon.2023.107922
- Gunawardena J, Egodawatta P, Ayoko G, Goonetilleke A (2012) Role of traffic in atmospheric accumulation of heavy metals and polycyclic aromatic hydrocarbons. Atmospheric Environment 54: 502-510. https://doi.org/10.1016/j.atmosenv.2012.02.058

- Guo Q, Chen A, Crockett EH, Atkins J, Chen X, Fei S (2023) Integrating gradient with scale in ecological and evolutionary studies. Ecology 104 (4). https://doi.org/10.1002/ecy.3982
- Guzmán P, Benítez Á, Carrión-Paladines V, Salinas P, Cumbicus N (2022) Elevation and Soil Properties Determine Community Composition, but Not Vascular Plant Richness in Tropical Andean Roadside. Forests 13 (5). https://doi.org/10.3390/f13050685
- Hadjibiros K (2013) Ecology and Applied Environmental Science. 1. CRC Press, Boca Raton. URL: https://www.taylorfrancis.com/books/9780429071546
- Homyack J, O'Bryan C, Thornton J, Baldwin R (2014) Anuran assemblages associated with roadside ditches in a managed pine landscape. Forest Ecology and Management 334: 217-231. https://doi.org/10.1016/j.foreco.2014.08.035
- Homyack J, O'Bryan C, Thornton J, Baldwin R (2016) Community occupancy of herpetofauna in roadside ditches in a managed pine landscape. Forest Ecology and Management 361: 346-357. https://doi.org/10.1016/j.foreco.2015.11.037
- Honour S, Bell JNB, Ashenden T, Cape JN, Power S (2009) Responses of herbaceous plants to urban air pollution: Effects on growth, phenology and leaf surface characteristics. Environmental Pollution 157 (4): 1279-1286. https://doi.org/10.1016/j.envpol.2008.11.049
- Hovd H, Skogen A (2005) Plant species in arable field margins and road verges of central Norway. Agriculture, Ecosystems & Environment 110 (3-4): 257-265. https://doi.org/10.1016/j.agee.2005.04.013
- IPCC (2023) IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. Intergovernmental Panel on Climate Change (IPCC). Edition: First. https://doi.org/10.59327/IPCC/AR6-9789291691647
- Jakobsson S, Bernes C, Bullock J, Verheyen K, Lindborg R (2018) How does roadside vegetation management affect the diversity of vascular plants and invertebrates? A systematic review. Environmental Evidence 7 (1). https://doi.org/10.1186/s13750-018-0129-z
- Jimenez MD, Ruiz-Capillas P, Mola I, Pérez-Corona E, Casado MA, Balaguer L (2013) SOIL DEVELOPMENT AT THE ROADSIDE: A CASE STUDY OF A NOVEL ECOSYSTEM. Land Degradation & Development 24 (6): 564-574. https://doi.org/10.1002/ldr.1157
- Ji S, Jiang Z, Li L, Li C, Zhang Y, Ren S, Ping X, Cui S, Chu H (2017) Impact of different road types on small mammals in Mt. Kalamaili Nature Reserve. Transportation Research Part D: Transport and Environment 50: 223-233. https://doi.org/10.1016/j.trd.2016.11.006
- Johnston FM, Johnston SW (2004) Impacts of Road Disturbance on Soil Properties and on Exotic Plant Occurrence in Subalpine Areas of the Australian Alps. Arctic, Antarctic, and Alpine Research 36 (2): 201-207. https://doi.org/10.1657/1523-0430(2004)036[0201:IORDOS]2.0.CO;2
- Joly M, Bertrand P, Gbangou R, White M, Dubé J, Lavoie C (2011) Paving the Way for Invasive Species: Road Type and the Spread of Common Ragweed (*Ambrosia artemisiifolia*). Environmental Management 48 (3): 514-522. https://doi.org/10.1007/s00267-011-9711-7

- Kalwij J, Milton S, McGeoch M (2008) Road verges as invasion corridors? A spatial hierarchical test in an arid ecosystem. Landscape Ecology 23 (4): 439-451. https://doi.org/10.1007/s10980-008-9201-3
- Karim MN, Mallik A (2008) Roadside revegetation by native plants. Ecological Engineering 32 (3): 222-237. https://doi.org/10.1016/j.ecoleng.2007.11.003
- Kayhanian M, Fruchtman B, Gulliver r, Montanaro C, Ranieri E, Wuertz S (2012) Review of highway runoff characteristics: Comparative analysis and universal implications. Water Research 46 (20). https://doi.org/10.1016/j.watres.2012.07.026
- Kroeger S, Hanslin H, Lennartsson T, D'Amico M, Kollmann J, Fischer C, Albertsen E, Speed JM (2022) Impacts of roads on bird species richness: A meta-analysis considering road types, habitats and feeding guilds. Science of The Total Environment 812 https://doi.org/10.1016/j.scitotenv.2021.151478
- Lange S, Mockford A, Burkhard B, Müller F, Diekötter T (2023) As green infrastructure, linear semi-natural habitats boost regulating ecosystem services supply in agriculturally-dominated landscapes. One Ecosystem 8 https://doi.org/10.3897/oneeco.8.e108540
- Laurance W, Croes B, Guissouegou N, Buij R, Dethier M, Alonso A (2008) Impacts of Roads, Hunting, and Habitat Alteration on Nocturnal Mammals in African Rainforests. Conservation Biology 22 (3): 721-732. https://doi.org/10.1111/j.1523-1739.2008.00917.x
- Lee M, Power S (2013) Direct and indirect effects of roads and road vehicles on the plant community composition of calcareous grasslands. Environmental Pollution 176: 106-113. https://doi.org/10.1016/j.envpol.2013.01.018
- Lemke A, Kowarik I, von der Lippe M (2019) How traffic facilitates population expansion of invasive species along roads: The case of common ragweed in Germany. Journal of Applied Ecology 56 (2): 413-422. https://doi.org/10.1111/1365-2664.13287
- Lerat-Hardy A, Coynel A, Schäfer J, Marache A, Pereto C, Bossy C, Capdeville M, Granger D (2022) Impacts of Highway Runoff on Metal Contamination Including Rare Earth Elements in a Small Urban Watershed: Case Study of Bordeaux Metropole (SW France). Archives of Environmental Contamination and Toxicology 82 (2): 206-226. https://doi.org/10.1007/s00244-021-00816-4
- Liu Z, Yang Y, Ji S, Dong D, Li Y, Wang M, Han L, Chen X (2021) Effects of Elevation and Distance from Highway on the Abundance and Community Structure of Bacteria in Soil along Qinghai-Tibet Highway. International Journal of Environmental Research and Public Health 18 (24). https://doi.org/10.3390/ijerph182413137
- Lucey A, Barton S (2011) Public Perception and Sustainable Management Strategies for Roadside Vegetation. Transportation Research Record: Journal of the Transportation Research Board 2262 (1): 164-170. https://doi.org/10.3141/2262-16
- Maes J, Driver A, Czúcz B, Keith H, Jackson B, Nicholson E, Dasoo M (2020) A review of ecosystem condition accounts: lessons learned and options for further development. One Ecosystem 5: e53485. https://doi.org/10.3897/oneeco.5.e53485
- Maes J, Bruzón A, Barredo J, Vallecillo S, Vogt P, Rivero IM, Santos-Martín F (2023) Accounting for forest condition in Europe based on an international statistical standard. Nature Communications 14 (1). https://doi.org/10.1038/s41467-023-39434-0
- Marche B, Camargo M, Bautista Rodriguez SC, Chaudron C, Mayer F, Bachmann C (2022) Qualitative sustainability assessment of road verge management in France: An approach from causal diagrams to seize the importance of impact pathways. Environmental Impact Assessment Review 97 https://doi.org/10.1016/j.eiar.2022.106911

- Marsh D (2007) Edge Effects of Gated and Ungated Roads on Terrestrial Salamanders. The Journal of Wildlife Management 71 (2): 389-394. https://doi.org/10.2193/2005-556
- Maynard R, Aall N, Saenz D, Hamilton P, Kwiatkowski M (2016) Road-Edge Effects on Herpetofauna in a Lowland Amazonian Rainforest. Tropical Conservation Science 9 (1): 264-290. https://doi.org/10.1177/194008291600900114
- McGrath DM, Henry J (2015) GETTING TO THE ROOT OF TREE STRESS ALONG HIGHWAYS©. Acta Hortic. 1085: 109-118. https://doi.org/10.17660/ActaHortic.2015.1085.20
- McPhillips L, Groffman P, Schneider R, Walter MT (2016) Nutrient Cycling in Grassed Roadside Ditches and Lawns in a Suburban Watershed. Journal of Environmental Quality 45 (6): 1901-1909. https://doi.org/10.2134/jeq2016.05.0178
- Mehmood Z, Hasnain A, Luqman M, Muhammad S, Dhital NB, John A, Iqbal M, Ejaz A, Tufail M, Harma -, Yang H, Awan MUF (2023) Assessment of Air Pollution Tolerance and Physicochemical Alterations of *Alstonia* Scholaris along Roadsides of Lahore, Pakistan. Aerosol and Air Quality Research 23 (7). https://doi.org/10.4209/aaqr.230038
- Mehmood Z, Yang H, Awan MUF, Ahmed U, Hasnain A, Luqman M, Muhammad S, Sardar AA, Chan T, Sharjeel A (2024) Effects of Air Pollution on Morphological, Biochemical, DNA, and Tolerance Ability of Roadside Plant Species. Sustainability 16 (8). https://doi.org/10.3390/su16083427
- Mills S, Mamo M, Ruis S, Blanco-Canqui H, Schacht W, Awada T, Li X, Sutton P (2021) Soil properties limiting vegetation establishment along roadsides. Journal of Environmental Quality 50 (1): 110-121. https://doi.org/10.1002/jeq2.20184
- Modlingerová V, Száková J, Sysalová J, Tlustoš P (2012) The effect of intensive traffic on soil and vegetation risk element contents as affected by the distance from a highway. Plant, Soil and Environment 58 (8): 379-384. https://doi.org/10.17221/309/2012-PSE
- Moher D, Liberati A, Tetzlaff J, Altman DG, for the PRISMA Group (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 339 (jul21 1). https://doi.org/10.1136/bmj.b2535
- Molina JA, Martín-Sanz JP, Casermeiro MÁ, Quintana JR (2024) Soil depth and vegetation type influence ecosystem functions in urban greenspaces. Applied Soil Ecology 194 URL: https://linkinghub.elsevier.com/retrieve/pii/S0929139323004079
- Monasterolo M, Poggio S, Medan D, Devoto M (2020) Wider road verges sustain higher plant species richness and pollinator abundance in intensively managed agroecosystems. Agriculture, Ecosystems & Environment 302 https://doi.org/10.1016/j.agee.2020.107084
- Morelli F, Beim M, Jerzak L, Jones D, Tryjanowski P (2014) Can roads, railways and related structures have positive effects on birds? – A review. Transportation Research Part D: Transport and Environment 30: 21-31. https://doi.org/10.1016/j.trd.2014.05.006
- Motti R, Zotti M, Bonanomi G, Cozzolino A, Stinca A, Migliozzi A (2021) Climatic and anthropogenic factors affect *Ailanthus altissima* invasion in a Mediterranean region. Plant Ecology 222 (12): 1347-1359. https://doi.org/10.1007/s11258-021-01183-9
- Neher D, Asmussen D, Lovell ST (2013) Roads in northern hardwood forests affect adjacent plant communities and soil chemistry in proportion to the maintained roadside area. Science of The Total Environment 449: 320-327. https://doi.org/10.1016/j.scitotenv.2013.01.062
- Neher D, Williams K, Lovell ST (2017) Environmental indicators reflective of road design in a forested landscape. Ecosphere 8 (3). https://doi.org/10.1002/ecs2.1734

- Niemeijer D, de Groot R (2008) A conceptual framework for selecting environmental indicator sets. Ecological Indicators 8 (1): 14-25. https://doi.org/10.1016/j.ecolind.2006.11.012
- Nikolaeva O, Karpukhin M, Streletskii R, Rozanova M, Chistova O, Panina N (2021) Linking pollution of roadside soils and ecotoxicological responses of five higher plants. Ecotoxicology and Environmental Safety 208 URL: https://linkinghub.elsevier.com/retrieve/pii/S0147651320314238
- Odum EP, Barrett G (2005) Fundamentals of ecology . 5th. Thomson Brooks/Cole, 598 pp.
- Pasquier A, André M (2017) Considering criteria related to spatial variabilities for the assessment of air pollution from traffic. Transportation Research Procedia 25: 3354-3369. https://doi.org/10.1016/j.trpro.2017.05.210
- Pereira HM, Ferrier S, Walters M, Geller GN, Jongman RH, et al. (2013) Essential Biodiversity Variables. American Association for the Advancement of Science URL: https://www.jstor.org/stable/23337854
- Peter L (1993) Emissions and air pollution concentrations of nitrogen oxides caused by a German motorway. Science of The Total Environment https://doi.org/10.1016/0048-9697(93)90345-7
- Phillips B, Bullock J, Osborne J, Gaston K (2020a) Ecosystem service provision by road verges. Journal of Applied Ecology 57 (3): 488-501. https://doi.org/10.1111/1365-2664.13556
- Phillips B, Wallace C, Roberts B, Whitehouse A, Gaston K, Bullock J, Dicks L, Osborne J (2020b) Enhancing road verges to aid pollinator conservation: A review. Biological Conservation 250 https://doi.org/10.1016/j.biocon.2020.108687
- Pourrezaei J, Khajeddin SJ, Karimzadeh H, Vahabi M, Mozaffarian V, Esfahani MT (2020) Effects of road features on the phytogeographical characteristics of plant species on natural-area roadsides. Folia Geobotanica 55 (4): 365-379. https://doi.org/10.1007/s12224-020-09382-4
- Ramísio P, Arezes D, Pinto LC (2021) A co-financing model for the mitigation of highway runoff pollution. Journal of Environmental Management 289 https://doi.org/10.1016/j.jenvman.2021.112432
- Rotholz E, Mandelik Y (2013) Roadside habitats: effects on diversity and composition of plant, arthropod, and small mammal communities. Biodiversity and Conservation 22 (4): 1017-1031. https://doi.org/10.1007/s10531-013-0465-9
- Rudi G, Bailly J, Caraglio Y, Dollinger J, Vinatier F (2022) Influence of maintenance practices on hydraulic functions of ditches: A trait-based approach. Ecohydrology 15 (8). https://doi.org/10.1002/eco.2464
- Ruiz-Capillas P, Mata C, Malo J (2013) Road verges are refuges for small mammal populations in extensively managed Mediterranean landscapes. Biological Conservation 158: 223-229. https://doi.org/10.1016/j.biocon.2012.09.025
- Safratowich B, Linz G, Bleier W, Homan HJ (2008) Avian Use of Rural Roadsides with Cattail (*Typha* spp.). The American Midland Naturalist 159 (1): 162-171. URL: https://www.jstor.org/stable/20491319
- Secco H, da Costa VO, Guerreiro M, Gonçalves PR (2022) Evaluating impacts of road expansion on porcupines in a biodiversity hotspot. Transportation Research Part D: Transport and Environment 102 https://doi.org/10.1016/j.trd.2021.103151

- Shahrukh S, Hossain SA, Huda MN, Moniruzzaman M, Islam MM, Shaikh MAA, Hossain ME (2023) Air pollution tolerance, anticipated performance, and metal accumulation indices of four evergreen tree species in Dhaka, Bangladesh. Current Plant Biology 35-36 https://doi.org/10.1016/j.cpb.2023.100296
- Siddaway A, Wood A, Hedges L (2019) How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses. Annual Review of Psychology 70 (1): 747-770. https://doi.org/10.1146/annurev-psych-010418-102803
- Spellerberg I (1998) Ecological effects of roads and traffic: a literature review: Ecological effects of roads. Global Ecology and Biogeography 7 (5): 317-333. https://doi.org/10.1046/j.1466-822x.1998.00308.x
- Streeter M, Schilling K (2020) Assessing and mitigating the effects of agricultural soil erosion on roadside ditches. Journal of Soils and Sediments 20 (1): 524-534. https://doi.org/10.1007/s11368-019-02379-3
- Sun P, Yang J, Wu Y, Liu X, Huang Y, He E, He T, Liu M (2023) Spatial modeling and source identification of PAHs in soils and roadside dusts from Hangzhou, a new first-tier megcity of China. Journal of Hazardous Materials 460 https://doi.org/10.1016/j.jhazmat.2023.132366
- Taiwo AM (2017) Characteristics of particulate matter collected at an urban background site and a roadside site in Birmingham, United Kingdom. Atmósfera 30 (4): 323-335. https://doi.org/10.20937/ATM.2017.30.04.04
- Tatariw C, Mason O, Mortazavi B (2021) Ditching Nutrients: Roadside Drainage Networks are Hotspots for Microbial Nitrogen Removal. Journal of Geophysical Research: Biogeosciences 126 (7). https://doi.org/10.1029/2020JG006115
- Tikka P, Högmander H, Koski P (2001) Road and railway verges serve as dispersal corridors for grassland plants. Landscape Ecology 16 (7): 659-666. https://doi.org/10.1023/A:1013120529382
- Tilman D, Knops J, Wedin D, Reich P, Ritchie M, Siemann E (1997) The influence of functional diversity and composition on ecosystem processes. Science 277 (5330): 1300-1302.
- Truscott AM, Palmer SC, McGowan GM, Cape JN, Smart S (2005) Vegetation composition of roadside verges in Scotland: the effects of nitrogen deposition, disturbance and management. Environmental Pollution 136 (1): 109-118. https://doi.org/10.1016/j.envpol.2004.12.009
- Tsunokawa K, Hoban C (Eds) (1997) Roads and the environment: A handbook. The World Bank.
- Twerd L, Sobieraj-Betlińska A, Szefer P (2021) Roads, railways, and power lines: Are they crucial for bees in urban woodlands? Urban Forestry & Urban Greening 61 https://doi.org/10.1016/j.ufug.2021.127120
- United Nations et al (2021) System of Environmental-Economic Accounting— Ecosystem Accounting (SEEA EA). White cover publication, pre-edited text subject to official editing. URL: https://seea.un.org/ecosystem-accounting
- Vallecillo Rodriguez S, Maes J, Teller A, Babi Almenar J, Barredo Cano JI, Trombetti M, Abdul M, Paracchini M, Carré A, Addamo A, Czucz B, Zulian G, Marando F, Erhard M, Liquete Garcia MD, Romao C, Polce C, Pardo Valle A, Jones A, Zurbaran-Nucci M, Nocita M, Vysna V, De Jesus Cardoso A, Gervasini E, Magliozzi C, Baritz R, Barbero M, Andre V, Kokkoris IP, Dimopoulos P, Kovacevic V, Gumbert A (2022) EU-wide

methodology to map and assess ecosystem condition. Publications Office of the European Union. https://doi.org/10.2760/13048

- van Strien M, Grêt-Regamey A (2025) Global expansion of the ecological impact of extra-urban road traffic. Nature Sustainability1-10. https://doi.org/10.1038/s41893-025-01637-2
- Vasconcelos P, Araújo G, Bruna E (2014) The role of roadsides in conserving Cerrado plant diversity. Biodiversity and Conservation 23 (12): 3035-3050. https://doi.org/10.1007/s10531-014-0762-y
- Vona-Túri D, Szmatona-Túri T, Kiss B (2017) Effects of roads and adjacent areas on diversity of terrestrial isopods of Hungarian highway verges. Biologia 72 (12): 1486-1493. https://doi.org/10.1515/biolog-2017-0160
- Vona-Túri D (2019) Invasive occurrence and abundance changes of Armadillidium vulgare (Latreille, 1804) in Hungarian roadside verges. Periodicum Biologorum 120 (2-3): 91-103. https://doi.org/10.18054/pb.v120i2-3.5632
- Wang T, Zhao J, Liu Y, Peng J, Wu L, Mao H (2022) PM2.5-Bound Polycyclic Aromatic Hydrocarbons (PAHs), Nitrated PAHs (NPAHs) and Oxygenated PAHs (OPAHs) in Typical Traffic-Related Receptor Environments. Journal of Geophysical Research: Atmospheres 127 (5). https://doi.org/10.1029/2021JD035951
- Watkins R, Chen J, Pickens J, Brosofske K (2003) Effects of Forest Roads on Understory Plants in a Managed Hardwood Landscape. Conservation Biology 17 (2): 411-419. https://doi.org/10.1046/j.1523-1739.2003.01285.x
- Wawer M, Magiera T, Ojha G, Ojha G, Bućko M, Kusza G (2015) Characteristics of current roadside pollution using test-monitoring plots. Science of The Total Environment 505: 795-804. https://doi.org/10.1016/j.scitotenv.2014.10.025
- Wei C, Wang M (2020) Spatial distribution of greenhouse gases (CO2 and CH4) on expressways in the megacity Shanghai, China. Environmental Science and Pollution Research 27 (25): 31143-31152. https://doi.org/10.1007/s11356-020-09372-1
- Wellicome T, Kardynal K, Franken R, Gillies C (2014) Off-road sampling reveals a different grassland bird community than roadside sampling: implications for survey design and estimates to guide conservation. Avian Conservation and Ecology 9 (1). https://doi.org/10.5751/ACE-00624-090104
- Willmert H, Osso J, Twiss M, Langen T (2018) Winter road management effects on roadside soil and vegetation along a mountain pass in the Adirondack Park, New York, USA. Journal of Environmental Management 225: 215-223. https://doi.org/10.1016/j.jenvman.2018.07.085
- Yackinous WS (2015) Understanding complex ecosystem dynamics: A systems and engineering perspective. Academic Press.
- Zeng S, Zhang T, Gao Y, Li B, Fang C, Flory SL, Zhao B (2012) Road effects on vegetation composition in a saline environment. Journal of Plant Ecology 5 (2): 206-218. https://doi.org/10.1093/jpe/rtr014
- Zhao Z, Hazelton P (2016) Evaluation of accumulation and concentration of heavy metals in different urban roadside soil types in Miranda Park, Sydney. Journal of Soils and Sediments 16 (11): 2548-2556. https://doi.org/10.1007/s11368-016-1460-z
- Zhu X, Lu K, Peng Z, He H, Xu S (2022) Spatiotemporal variations of carbon dioxide (CO2) at Urban neighborhood scale: Characterization of distribution patterns and contributions of emission sources. Sustainable Cities and Society 78 https://doi.org/10.1016/j.scs.2021.103646

Supplementary materials

Suppl. material 1: Data retrieved for interactions

Authors: Ziadany Mayoral Solis
Data type: occurrences
Brief description: This data reports the interactions between the variables as well as the interactions between pressures and variables from the literature corpus analysed.
Download file (27.57 kb)

Suppl. material 2: Variable definitions

Authors: Ziadany Mayoral, Clémence Chaudron, Brunelle Marche, Mauricio Camargo
Data type: Text
Brief description: Variable definitions and in-depth information from the analysed literature.
Download file (146.89 kb)

Suppl. material 3: Process for core variables selection

Authors: Ziadany Mayoral, Clémence Chaudron, Brunelle Marche, Mauricio Camargo
Data type: Text
Download file (999.99 kb)

Endnotes

*1 A gradient is a continuous variation of a variable (physical or biological) that can exist at different scales (the extent of a study in terms of space, time or biological organisation). Scales may encompass different gradients (Guo et al. 2023).

*2 Zones not directly influenced by road infrastructures and their associated impacts.