

# Global biodiversity impact spillovers of national transportation systems

Venla A. Leppilampi<sup>a,b</sup>, Janne S. Kotiaho<sup>a,b</sup>, Stefan Baumeister<sup>b,c</sup>, Essi Järvinen<sup>a,b</sup> & Sami El Geneidy<sup>b,c</sup>

<sup>a</sup> Department of Biological and Environmental Science, University of Jyväskylä, P.O. Box 35, N40014 Jyväskylä, Finland

<sup>b</sup> School of Resource Wisdom, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland

<sup>c</sup> School of Business and Economics, University of Jyväskylä, P.O. Box 35, N40014 Jyväskylä, Finland

\*Corresponding author at: Department of Biological and Environmental Science, University of Jyväskylä, P.O. Box 35, N40014 Jyväskylä, Finland and School of Resource Wisdom, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland.

*E-mail address:* [venla.a.leppilampi@jyu.fi](mailto:venla.a.leppilampi@jyu.fi) (V.A. Leppilampi)

ORCID: <https://orcid.org/0009-0004-5882-5571>

## Abstract

Transportation systems' value chain biodiversity impacts remain poorly understood. Here, we quantify the life cycle biodiversity and carbon footprints of Finland's national transportation system, covering traffic, transport infrastructure, vehicle production and maintenance. Using detailed national data and the Biodiversity Equivalent Impact Assessment method, we estimate a biodiversity footprint corresponding to a potential extinction risk for approximately 0.1 % of global species, and a carbon footprint of 677 Mt kg CO<sub>2</sub>eq. Passenger car traffic and roads were the largest contributors to both footprints, while climate change was the dominant biodiversity loss driver. Traffic lanes generated life cycle biodiversity impacts 45 times larger

than impacts from local land-use change, demonstrating significant global biodiversity spillovers. Vehicle electrification can substantially reduce both footprints, whereas biofuel adoption may increase biodiversity loss. Integrating life cycle biodiversity and climate impacts assessments into transport policy is therefore essential to avoid overlooking global impacts and avoid unintended biodiversity-climate trade-offs.

## Keywords

biodiversity footprint; biodiversity impact; carbon footprint; transportation systems; life cycle assessment

## 1. Introduction

Transportation systems have well-established local impacts on biodiversity and make substantial contributions to greenhouse gas emissions (Borgelt et al., 2024; Chen and Koprowski, 2016; Coffin, 2007; Fuentes-Montemayor, 2009; Hulme, 2009; Jones et al., 2000; Muñoz et al., 2015; van Strien and Grêt-Regamey, 2025). Yet the global life cycle biodiversity impacts embedded in value chains of transport infrastructure and traffic remain poorly characterized, despite national transportation systems depending on fuels, vehicles and infrastructure which production and maintenance generate biodiversity pressures across distant regions and ecosystems (Wilting et al., 2017; Wilting and van Oorschot, 2017). This is a major blind spot in sustainability assessments of transportation systems which may contribute to global biodiversity loss in ways that are not captured by local impact assessments or carbon accounting alone.

This gap matters because biodiversity is declining at an unprecedented rate in human history (IPBES, 2019), driven by land- and sea-use change, direct exploitation of organisms, climate change, pollution and invasive alien species (Díaz et al., 2019). Among these drivers, climate change is becoming increasingly important (Román-Palacios and Wiens, 2020; Urban, 2024),

largely as a result of anthropogenic greenhouse gas emissions (IPCC, 2023; Ripple et al., 2023), to which transport is a major and growing contributor (IEA, 2026; Jaramillo et al., 2022). Despite international commitments to mitigate climate change and halt biodiversity loss, neither global emissions nor biodiversity decline shows clear signs of slowing (CBD, 2020; IPBES, 2019). These intertwined crises call for assessments that consider climate and biodiversity impacts together, particularly in sectors where mitigation choices may create synergies or trade-offs between the two.

Transportation is one such sector. It is essential to modern societies, enabling the movement of people and goods through networks of vehicles, infrastructure, energy systems and services (Cascetta, 2001; Traficom, 2024). Yet transport policy and assessment remain dominated by climate metrics (Azarkamand et al., 2020; Baumeister, 2019; Borken-Kleefeld et al., 2013; Dimoula et al., 2016; Hanson and Noland, 2015; Postorino and Mantecchini, 2014), even though mitigation options differ in their biodiversity consequences. Electrification may reduce both carbon and biodiversity footprints when powered by low-impact electricity, whereas large-scale reliance on biofuels may reduce apparent climate impacts while increasing biodiversity pressures through land use, water depletion or pollution. Assessing transport systems through greenhouse gas emissions alone may therefore obscure biodiversity impacts, misidentify solutions and shift environmental burdens across regions and ecosystems.

Previous studies have examined life-cycle biodiversity impacts of transport systems from specific perspectives (Borgelt et al., 2024; Bull et al., 2022; Kulionis et al., 2024; Wilting et al., 2017; Wilting and van Oorschot, 2017), but an integrated nationwide assessment of both biodiversity and climate impacts remains lacking. The national scale is particularly relevant because many decisions on transport policies seem to have most relevance nationally (Axsen et al., 2020; Jaccard et al., 2019), while their biodiversity consequences may extend far beyond national borders.

Here we quantify the life cycle biodiversity and climate impacts of Finland's national transportation system. Finland provides a relevant case of an industrialized high-income country with both urban and rural transport needs, extensive transport infrastructure and a changing vehicle and motive power mix. We ask: 1) what are the biodiversity and climate impacts of a national transportation system and what are they composed of, 2) how much mitigation potential different transport modes and motive powers would have offered relative to observed development, and 3) how the life cycle biodiversity impacts of traffic lanes compare with their local biodiversity impacts from land-use change.

## 2. Materials and methods

Biodiversity footprint assessment can be based on life cycle assessment (LCA) methods, environmentally extended input-output (EEIO) analysis or a hybrid-LCA approach, that combines the two (Crawford, 2008; Damiani et al., 2023; Marques et al., 2017). We assessed biodiversity and carbon footprints using the Biodiversity Equivalent Impact Assessment method, BIOVALENT (El Geneidy et al., 2026), which builds on established life cycle assessment approaches (Hellweg et al., 2023; Hellweg and Milà i Canals, 2014). Consequently, the drivers of biodiversity loss arising from human activities and their eventual impacts on biodiversity can be modelled.

In the assessment, information is needed of 1) the amount and type of activities, 2) the amount and type of the driver of biodiversity loss caused by the activities, 3) geographical location of the drivers of biodiversity loss and 4) the spatially explicit impacts on biodiversity caused by the different drivers (El Geneidy et al., 2026).

## 2.1. Finnish transportation system and system boundaries

Finland is a country located in Northern Europe. Its total area is 338 491 km<sup>2</sup>, of which 304 000 km<sup>2</sup> is land area (Statistics Finland, 2025a). In 2025, Finland had 5.6 million inhabitants (Statistics Finland, 2026a).

Transportation systems consist of traffic lanes, all modes of transport, transport services, telecommunications networks, vehicles and the systems controlling the traffic (Traficom, 2024). Based on this definition, we outlined the system boundaries of the research. The sub-systems considered were 1) vehicles, 2) domestic passenger and freight traffic and 3) transport infrastructure. This formed the first, high level definition of the system boundary. As the analysis of data availability proceeded, the system boundary was refined in more detail. A more specific description of the system boundaries is provided in Fig. B.1.

Traffic control systems and management and telecommunication systems were scoped out of this study. Foreigners' travel to Finland, Finnish residents' travel abroad, and trips and freight abroad by vehicles registered in Finland were also outside the system boundary. National transportation statistics do not identify vehicle registration country (Niinikoski and Moilanen, 2017) or traveller's nationality and thus, travel activity by domestic or foreign travellers cannot be separated from the datasets. However, trips abroad by vehicles in the Finnish register should be included in Finnish traffic statistics. Because these distinctions cannot be made, the resulting inaccuracies have been reported to partially offset one another (Niinikoski and Moilanen, 2017). As nationality specific travel cannot be distinguished from the transport statistics, the travelling of Finnish people abroad should be included in the biodiversity and carbon footprint of the country of destination.

International air transport and shipping were also excluded because they are not included in the Finnish emission calculations (Traficom, 2021) and are subject to separate international

climate goals (ICAO, 2026; IMO, 2026). In addition, transportation activities of defensive forces and border guard detachment were scoped out of this study, although including them in the future assessments would be important for facilitating sustainable transportation in these sectors as well.

### 2.3. Data collection

The data on amount and type of activities (i.e. consumption) of the Finnish transportation system were gathered from the open statistics of Statistics Finland (Statistics Finland, 2026b) and the Transport and Communications Agency, Traficom (Traficom, 2026). Also, reports published by transportation sector organisations were used and information requests were submitted when more specific data were needed. Technical details, such as battery weights and electricity consumption in PHEV transport were obtained from scientific or grey literature. Detailed references are given in Data Availability and Supplementary Methods.

The consumption data of the Finnish transportation system is fragmented (Fig. D.1), and thus, we used input data from different years. Most of the data on number of vehicles were from 2023 or 2024, whereas data on transport infrastructure, such as ports and railway stations, was from older national transport reports, as collecting exact activity data for each individual building was beyond the scope of this study. For the biodiversity and carbon footprint time series of traffic, we collected data from 2016 – 2023 from national transport statistics. Specific data used in the assessment is provided in Data Availability and Supplementary Methods. In some cases, the input data were not directly applicable and required further processing. The details of the input data processing are provided in Supplementary Methods.

### 2.4. Modelling biodiversity impacts

We combined ecoinvent 3.10.1 Cutoff and APOS version (ecoinvent, 2016a, 2016b; Wernet et al., 2016) and the ReCiPe2016 v.1.03 Midpoint (H) method (Huijbregts et al., 2017) using

openLCA software version 2.4.1/2.5.0 to derive the characterization factors describing the amount and type of biodiversity loss drivers per unit of activity, as well as the geographical location of these drivers (El Geneidy et al., 2026; Huijbregts et al., 2017). Ecoinvent is a global life cycle inventory database providing supply chain data of different sectors' material and energy flows (Wernet et al., 2016). ReCiPe2016 is a life cycle impact assessment (LCIA) method providing harmonised implementation of cause-effect pathways for calculating characterization factors at midpoint and endpoint level (Huijbregts et al., 2017). Here we use ReCiPe only for the characterization of midpoint impacts.

Before the assessment, the consumption data were harmonized with the corresponding ecoinvent processes. The harmonization procedure is provided in Supplementary Table 2.

Biodiversity impacts were assessed across terrestrial, freshwater and marine ecosystems (El Geneidy et al., 2026). To create impact factors describing the environmental impact caused by biodiversity loss drivers per unit of activity, we used the LC-IMPACT method version 1.3 (El Geneidy et al., 2026; Verones et al., 2020a). LC-IMPACT provides regionalised characterization factors, expressed as potentially disappeared fraction of species (PDF) per unit of biodiversity loss driver for terrestrial, marine and freshwater ecosystems (Verones et al., 2020a). The regionalized midpoint characterization factors for each driver of biodiversity loss per unit of activity were multiplied by the corresponding PDF values for each driver and region.

We used Rstudio version 4.4.1. to create the impact factors. We used R-script generated by Peura and Leppilampi (2026). In total, we created impact factors for 113 processes to assess the biodiversity and carbon footprint of the Finnish transportation system. The impact factors are accessible in the Data Availability.

The impact factors were then multiplied by the corresponding activity data to derive a biodiversity footprint of each ecosystem type in PDFs. These ecosystem specific footprints

were then aggregated into a biodiversity footprint per activity category, using weights representing the share of all plant and animal species that exist in terrestrial, freshwater and marine ecosystems (El Geneidy et al., 2026; Román-Palacios et al., 2022), see equation (1) below. This spatially explicit indicator of potential global species loss combining biodiversity impacts across all ecosystem types is called the biodiversity equivalent, BDe (El Geneidy et al., 2026). Carbon footprints were expressed as carbon dioxide equivalents (CO<sub>2</sub>e).

$$BDe = PDF_{terrestrial} \times 0.801 + PDF_{freshwater} \times 0.0967 + PDF_{marine} \times 0.102 \quad (1)$$

It has been argued that biodiversity equivalent has similar desirable characteristics as carbon dioxide equivalent in a way that it enables measuring biodiversity impacts of human activities on a global level in a unified, globally comparable way (El Geneidy et al., 2026). Its values vary between 0–1, where zero indicates no risk of extinction and one that the fraction of global species in the risk of extinction is 100 %.

Because the biodiversity impacts of activities are measured on a global level i.e. impacts on all world species, BDe values are typically very small. For readability of the results, we use prefixes of scientific notations, in this case nano ( $n = 10^{-9}$ ). The BIOVALENT methodology is described in detail in El Geneidy et al. (2026).

#### 2.4.1 Environmental pressures

For terrestrial ecosystems, the environmental pressures included in the biodiversity footprint assessment were land occupation (m<sup>2</sup>), including annual and permanent crops, pasture, urban land use, extensive and intensive forestry, photochemical oxidant formation (kg NO<sub>x</sub> e) and terrestrial acidification (kg SO<sub>2</sub> e). For freshwater ecosystems, the environmental pressures were water depletion (m<sup>3</sup>) and freshwater eutrophication (kg P e). Climate change impacts (kg CO<sub>2</sub> e) were included in the biodiversity footprint of both terrestrial and freshwater ecosystems. The GHGs included in climate change impacts were carbon dioxide, nitrous oxide, and

methane. For marine ecosystems, the environmental pressure was marine eutrophication (kg N e).

The distribution of biodiversity impacts across drivers of biodiversity loss may change in future assessment as impacts of other biodiversity loss drivers, such as depletion of natural resources and invasive alien species can be included in the methodology.

#### 2.4.2 Vehicle production and maintenance

The assessment of vehicle production impacts were based on the total number of registered vehicles in each vehicle category, except for passenger cars, for which the assessment was based on the mass of the produced car (kg). The impact assessment of vehicle maintenance was based on the total number of registered vehicles in each vehicle category.

#### 2.4.3 Functional units and activity data of traffic operation

Traffic operation impacts were modelled using annual vehicle-kilometres travelled (VKT), passenger-kilometres travelled (PKT) or ton-kilometres travelled (TKT), depending on the transport mode. Accordingly, the functional unit of traffic operation was either kilometres, passenger-kilometres, or ton-kilometres. For biogas-powered passenger cars, the impacts were quantified per kilogram of produced biomethane (kg), while leisure boating impacts were based on fuel consumption (L).

#### 2.4.4 Well-to-wheel assessment

To avoid double counting between traffic operation, vehicle production and infrastructure, traffic impacts were assessed using a well-to-wheel (WTW) analysis, which includes the impacts of fuel production, transport and consumption (Orsi et al., 2016). Vehicle and infrastructure-related flows were removed from the corresponding ecoinvent transport processes in openLCA. The applied process modifications are provided in Supplementary Table 2.

#### 2.4.5 Annual and life cycle impacts of traffic

Traffic impacts were assessed at both annual and vehicle life cycle scales. For the annual assessment, VKT, TKT or PKT between 2016 – 2023 were multiplied by the corresponding impact factors to estimate yearly biodiversity and carbon footprints of traffic.

For the impact assessment of traffic over the life cycle of vehicles, a mean annual distance travelled of each transport mode was derived from transport statistics and applied to the expected life span of the corresponding vehicle type (Supplementary Table 3) to estimate the cumulative VKT (or PKT/TKT depending on the transport mode) during vehicle operation. These cumulative kilometres travelled were then multiplied by the corresponding ecosystem-specific impact factors for pollution and climate change.

Land use and water depletion impacts were estimated using the average annual kilometres travelled of each transport mode and multiplied by the respective impact factors. Unlike pollution and greenhouse gas emissions, which are directly related with transport activity, land use and water depletion impacts in the ecoinvent database are primarily associated with infrastructure and production systems that provide services over long periods of time. For example, land occupation is related to production facilities such as mineral extraction sites rather directly proportional to cumulative kilometres travelled. Similarly, water depletion associated with fuel consumption is primarily related to electricity production, whose infrastructure sites remain in operation for multiple years. Consequently, applying land use and water depletion impact factors to cumulative kilometres travelled over the assessment period could result in repeated allocation of impacts related to the same infrastructure, potentially leading to an overestimation of land use and water depletion impacts. However, the land use impacts of biofuels were estimated separately (see 2.4.6 Estimation of biofuel induced land use change impacts and Supplementary Methods).

#### 2.4.6 Estimation of biofuel induced land use change impacts

The land use impacts of biofuels arising from cumulative VKT during vehicle operation were assessed differently from those of passenger cars using fossil fuels. This was done because assuming that land use from biofuel consumption is non-cumulative would likely underestimate the impacts, as biofuel production is known to drive land use change and biodiversity loss (Elshout et al., 2014; Tudge, 2021).

We used country-level land occupation and transformation inventory data (Faragò et al., 2019) and combined it with ecoinvent land use data to estimate long-term changes in land use associated with biodiesel, bioethanol and biogas production. These adjusted land use values were then multiplied by characterization factors for land use from LC-IMPACT. The method and underlying assumptions are described in detail in Supplementary Methods.

#### 2.4.7 Comparison of the footprint of transport modes per passenger-kilometre

To estimate the biodiversity and climate impacts of different transport modes per passenger-kilometre, the footprints per kilometre driven for each vehicle type were divided by the average number of passengers per VKT. We estimated the average number of passenger per VKT for each transport mode,  $N_{pass./VKT}$ , in 2023 as follows:

$$N_{pass./VKT} = N_p / VKT_{tot} \quad (3)$$

Where  $N_p$  is the number of passengers per vehicle type in 2023 and  $VKT_{tot}$  is total vehicle kilometres driven per vehicle type in 2023.

The data were obtained from the national Public Transport Performance Statistics (Traficom, 2025). For trams we took an average of the passenger numbers in trams (streetcars) and light rail. For passenger cars, we used average passenger number in 2016 (Liikennevirasto, 2018), since no data were available for 2023.

#### 2.4.8 Transport scenarios

We created four scenarios for the footprints of passenger car transport for the years 2016 – 2023 and compared these with the historical, realized footprints.

The “Fossil fuel scenario” represents a situation in which only fossil petrol and diesel are used in passenger car transport. In this scenario, the estimated shares of passenger cars in transport ranged from 71-73 % for petrol and 27-29 % for diesel passenger cars. In the “electric-biodiesel scenario”, all passenger cars in traffic during the years 2016 – 2023 were assumed to be electric, except for diesel passenger cars, which use pure biodiesel. Here, the share of electric passenger ranged from 72-75 % and the share of diesel passenger cars ranged from 25-28 %. The detailed methods used to derive the shares are provided in Supplementary Methods. In the “Only biodiesel scenario” all passenger cars were diesel passenger car using pure biodiesel and in the “Only electric cars scenario” all passenger cars were electric.

To estimate the VKT by motive power in each scenario, the annual passenger car VKT for 2016 – 2023 was allocated to each motive power based on the scenario specific fleet shares. These VKTs were then multiplied by the corresponding impact factors to derive the biodiversity and carbon footprint for each scenario.

#### 2.4.9 Traffic lanes, lay-bys, and parking areas

Estimating the footprints of traffic lanes was based on the total length (km) and area (m<sup>2</sup>) of each lane type. For lay-bys and parking lots along roads, the impact assessment was based on their total area (m<sup>2</sup>).

#### 2.4.10 Transport stations

The assessment of the biodiversity and carbon footprints of Finnish transport stations was based on the number of stations, and for bus depots, railway and metro stations, on their total area (m<sup>2</sup>). For multi-storey car parks, the impact assessment was based on their total capacity (m<sup>3</sup>).

#### 2.4.11 Assessing biodiversity impacts of local land use

To estimate the magnitude of global spillover impacts from transport infrastructure, the biodiversity impacts associated with the local land use were assessed separately from the life cycle assessment. The life cycle footprint included value chain impacts from material extraction, production and transport, whereas the local footprint captured biodiversity loss from land use change caused by transportation infrastructure in Finland. To avoid double counting, land occupation input flows were removed from the corresponding ecoinvent processes in openLCA (see Supplementary Table 2).

The biodiversity impacts of local land use were quantified by multiplying the occupied area ( $\text{m}^2$ ) of traffic lanes, lay-bys, and parking lots, railway stations and bus depots by the characterization factor for urban land occupation, using the median value of Finland expressed in global PDF/ $\text{m}^2$  from LC-IMPACT. The global PDF indicator describes the share of world species potentially disappearing in terrestrial ecosystems after the conversion of natural habitat to the current land use type (Verones et al., 2020b), in this case, urban land use in Finland. Using global PDF to estimate the biodiversity footprint of local land use allows comparing the impacts with those arising from the value chains. For traffic green zones, impacts were estimated by taking an average of the characterization factor values for pasture and urban land occupation (global PDF/ $\text{m}^2$ , median value for Finland). Lastly, the PDF values of local land use were converted to biodiversity equivalents (BDe) by weighing them with the share of all plant and animal species that exist in terrestrial ecosystems (El Geneidy et al., 2026; Román-Palacios et al., 2022).

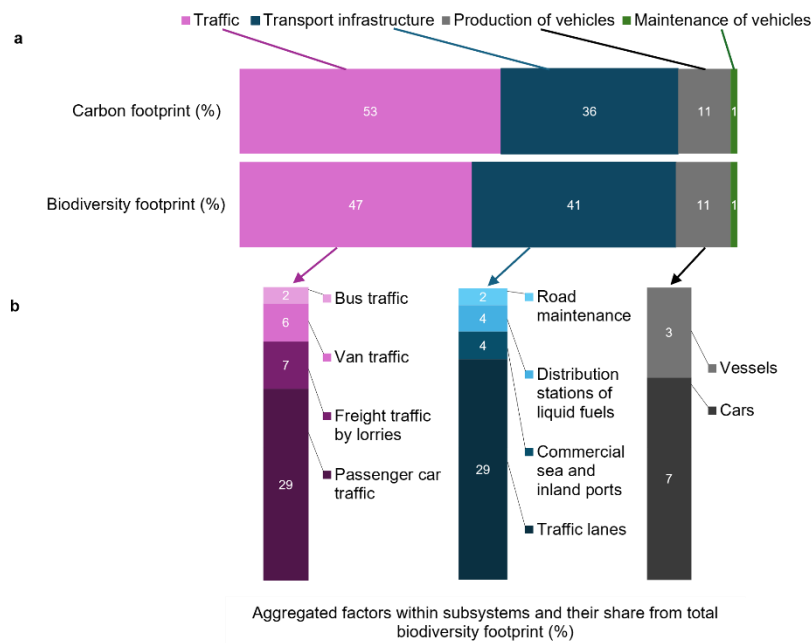
### 3. Results

#### 3.1. Traffic and transport infrastructure dominate national transport footprints

The Finnish transportation system had a total biodiversity footprint of 1,152,207 nano biodiversity equivalents (nBDe) and a carbon footprint of 677 Mt CO<sub>2</sub>e. This biodiversity footprint corresponds to an estimated potential extinction risk for approximately 0.1% of global species.

Traffic was the largest contributor to the biodiversity footprint, driven especially by passenger car use (Fig. 1a, 1b). Petrol and diesel passenger car traffic accounted for approximately 22 % and 6 % of the total biodiversity footprint, respectively, while all other passenger car traffic categories together contributed less than 1% (Table A.1). Transport infrastructure was the second largest contributor, with traffic lanes alone accounting for 29 % of the total biodiversity footprint (Fig. 1a,b and Table A.1). Vehicle production and maintenance contributed less than traffic and infrastructure, but cars were the dominant source within this subsystem (Fig 1b); in particular, petrol passenger car production accounted for approximately 4 % of the total biodiversity footprint (Table A.1).

The carbon footprint showed a similar overall pattern. Traffic was again the largest contributor, with passenger car traffic accounting for 33 % of the total carbon footprint of the Finnish transportation system (Fig. C.1). Transport infrastructure was the second largest contributor, with traffic lanes alone accounting for approximately 28 % of the total carbon footprint (Fig. C.1). Within vehicle production subsystem, cars were the dominant source, contributing approximately 7 % of the total carbon footprint, of which petrol passenger cars were again the major contributor, accounting for 4 % of the total carbon footprint (Table C.1 and Fig. C.1).



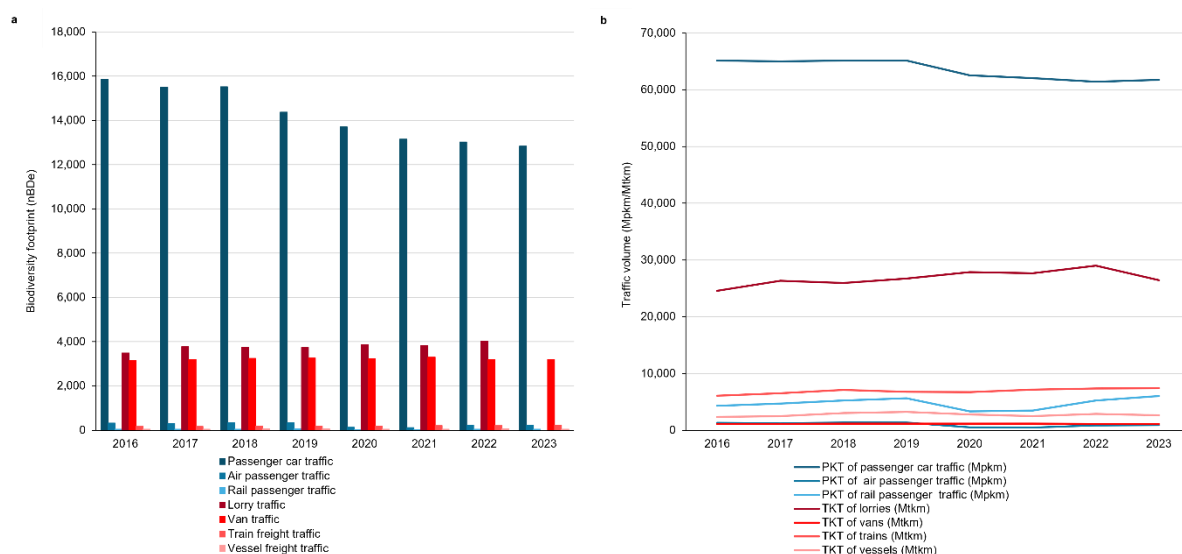
**Fig. 1: Biodiversity and carbon footprints of the Finnish transportation system. a,** Shares of the main subsystems in the total biodiversity and carbon footprints. **b)** Key contributors within subsystems and their shares of the total biodiversity footprint. Contributors accounting for less than 2% of the total biodiversity footprint are not shown. Vehicle maintenance accounted for only 1% of the total biodiversity footprint and is therefore omitted from panel b.

### 3.2. Passenger cars and lorries dominate traffic-related biodiversity footprints

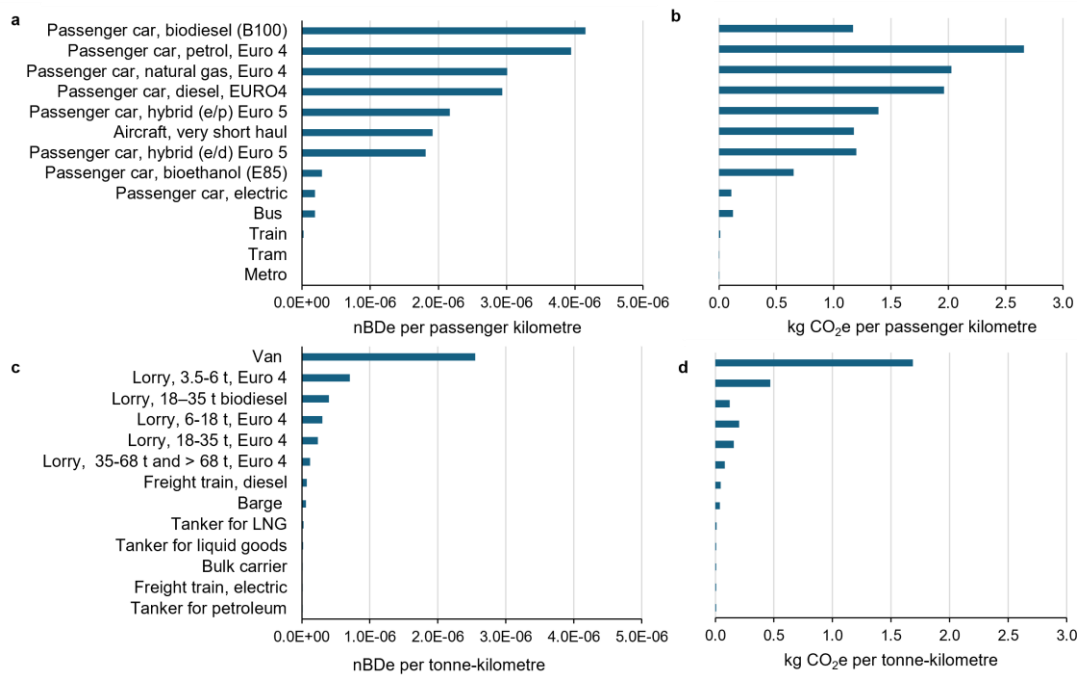
Passenger cars generated the largest biodiversity footprint among passenger transport modes between 2016 and 2023, although their footprint declined after 2018 (Fig. 2a). This dominant contribution reflected the high volume of passenger car traffic relative to other passenger transport modes (Fig. 2b). By contrast, passenger rail had the smallest biodiversity footprint despite being the second-largest passenger transport mode in terms of passenger-kilometres travelled, indicating a substantially lower biodiversity footprint per passenger-kilometre than road-based passenger transport (Fig. 2a, b and Fig 3a).

To make biodiversity and carbon intensities explicit across passenger transport modes and motive powers, we compared footprints per passenger-kilometre using average passenger occupancy in 2023. Diesel passenger cars fuelled with pure biodiesel had the highest biodiversity intensity (Fig. 3a), although their carbon intensity was lower than that of conventional fossil-fuel passenger cars (Fig. 3b). Fossil-fuel passenger cars generally had higher biodiversity and carbon intensities than public transport modes, electric passenger cars and bioethanol passenger cars (Fig. 3a,b). Public transport modes had among the lowest passenger kilometre impacts, with biodiversity and carbon intensities approximately 88 and 79 times lower, respectively, than those of petrol passenger cars.

In freight transport, lorries generated the largest total biodiversity footprint (Fig. 2a). Van traffic had the second largest freight-related footprint (Fig. 2a), but the highest biodiversity and carbon intensity per tonne-kilometre travelled (Fig 3c,d). Freight rail and vessel freight transport had a small biodiversity footprint even relative to their transport volume, translating into substantially lower biodiversity and carbon intensity than road freight (Fig. 2a,b and 3c,d).



**Fig. 2: Biodiversity footprint and traffic development of passenger and freight transport, 2016–2023.** **a**, Biodiversity footprint of passenger and freight transport. **b**, Development of passenger and freight transport volumes. PKT denotes passenger-kilometres travelled and TKT tonne-kilometres travelled. Mpkm and Mtkm denote million passenger-kilometres and million tonne-kilometres, respectively. Passenger rail includes train, tram and metro.



**Fig. 3: Biodiversity and carbon intensities of passenger and freight modes in 2023.** **a**, Biodiversity footprint intensity by vehicle type in passenger transport, expressed per passenger-kilometre. **b**, Carbon footprint intensity by vehicle type in passenger transport, expressed per passenger-kilometre. Train values represent the average impacts of regional and long-distance passenger rail. In plug-in hybrids, e/d denotes electricity-diesel and e/p electricity-petrol motive power. **c**, Biodiversity footprint intensity by vehicle type in freight transport, expressed per tonne-kilometre. **d**, Carbon footprint intensity by vehicle type in freight transport, expressed per tonne-kilometre.

### 3.3. Climate change is the largest driver of biodiversity loss across most transport subsystems

The relative importance of biodiversity loss drivers varied across ecosystem types and subsystems (Table 1). In terrestrial ecosystems, climate change accounted for the largest share of biodiversity impacts in all subsystems, ranging from 79% for transport infrastructure to 97% for traffic. In freshwater ecosystems, climate change dominated the biodiversity footprints of traffic and transport infrastructure, whereas water depletion was the largest driver of footprints from vehicle production and maintenance. The influence of climate change was particularly pronounced for traffic, where biodiversity impacts arise largely from energy use and associated greenhouse gas emissions, especially fossil fuel combustion. A detailed breakdown of the biodiversity impacts by drivers, subsystems, and contributors is provided in Table A.2.

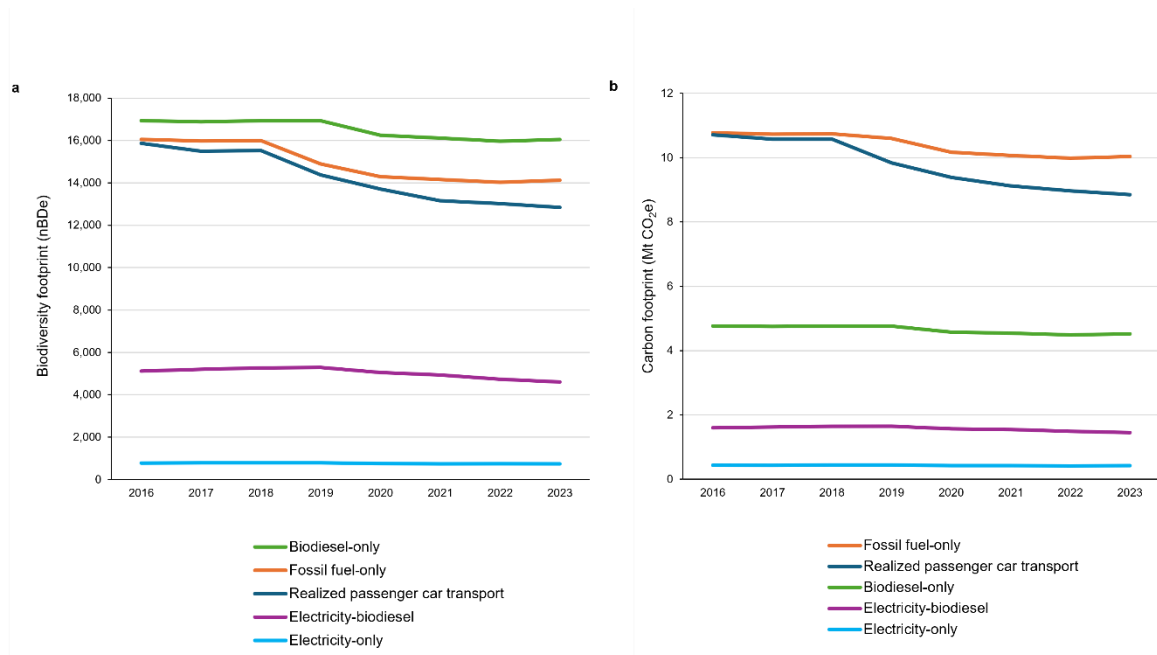
**Table 1: Relative contributions of biodiversity loss drivers to transport-related biodiversity impacts in terrestrial and freshwater ecosystems.** Values are shown by subsystem of the transport subsystem. Marine ecosystems are not shown because only pollution-related impacts could be assessed.

|                          | Terrestrial ecosystems |           |                | Freshwater ecosystems |           |                |
|--------------------------|------------------------|-----------|----------------|-----------------------|-----------|----------------|
|                          | Land use               | Pollution | Climate change | Water depletion       | Pollution | Climate change |
| Production, vehicles     | 3 %                    | 8 %       | 89 %           | 52 %                  | 20 %      | 28 %           |
| Maintenance, vehicles    | 7 %                    | 8 %       | 85 %           | 54 %                  | 13 %      | 33 %           |
| Traffic                  | 0.1 %                  | 3 %       | 97 %           | 1 %                   | 1 %       | 98 %           |
| Transport infrastructure | 9 %                    | 12 %      | 79 %           | 30 %                  | 11 %      | 58 %           |

### 3.4. Electrification reduces biodiversity and climate impacts, whereas biodiesel creates biodiversity trade-offs

The realized biodiversity and carbon footprints of passenger car traffic declined over time, reflecting increasing electrification and reduced vehicle-kilometres travelled (Fig. 4). Complete electrification of the passenger car fleet would have reduced the biodiversity and carbon footprints of passenger car traffic by 94 % and 84 %, respectively, relative to realized development. Although electric passenger car production had larger biodiversity and carbon footprints per vehicle than production of conventional vehicles, these production impacts were outweighed by substantially lower use-phase impacts under the Finnish electricity mix, even when battery production was included (Fig. C.2a, b).

The electricity-biodiesel scenario also had lower biodiversity and carbon footprints than both realized development and the fossil-fuel-only scenario (Fig. 4). By contrast, the biodiesel-only scenario reduced climate impacts relative to fossil-fuel passenger cars, but increased biodiversity impacts. Its biodiversity footprint exceeded that of all other scenarios, showing that climate-oriented fuel substitution can create substantial biodiversity trade-offs when land use, water depletion and pollution pressures are considered.

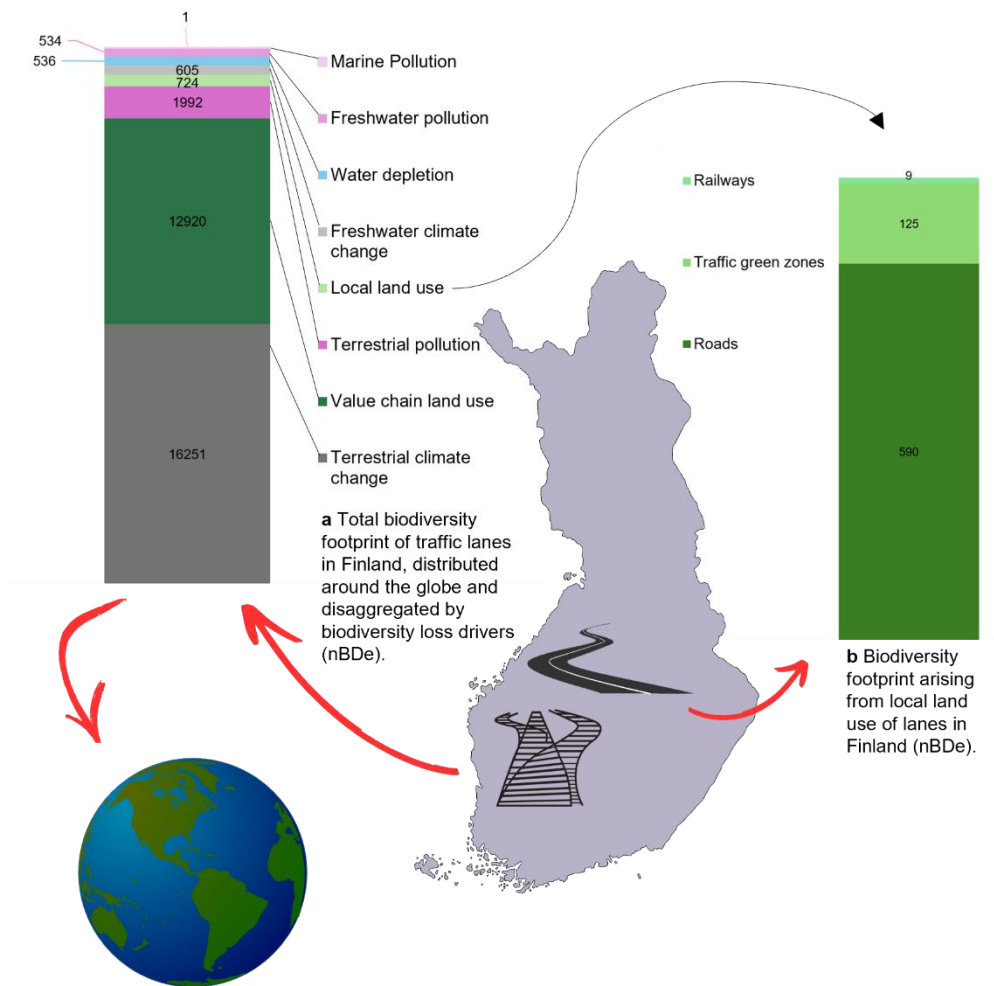


**Fig. 4: Biodiversity and carbon footprints of passenger car motive power scenarios, 2016–2023.** Scenario analysis comparing realized passenger-car traffic with fossil-fuel-only, electric-only, biodiesel-only and electric-biodiesel scenarios, using realized vehicle-kilometres travelled. **a**, Biodiversity footprints of scenarios. **b**, Carbon footprints of scenarios.

### 3.5. Value chain impacts of traffic lanes far exceed local land-use impacts

The life cycle biodiversity footprint of traffic lanes was approximately 45 times larger than their footprint from local land use. Value chain impacts were driven mainly by climate change, reflecting greenhouse gas emissions from fuel combustion in construction machinery and from the production of road materials such as clinker and pitch. Additional impacts arose from land use associated with landfill for inert material, forestry practises for energy production and gravel production (Fig. 5).

This comparison shows that local land-use assessments capture only a small fraction of the biodiversity impacts associated with traffic lanes. National transport infrastructure can therefore generate substantial global spillovers through on-site construction activities and the extraction, production and transport of construction materials.



**Fig. 5: Life cycle and local land use biodiversity footprints of traffic lanes in Finland. a,** Life cycle biodiversity footprint of traffic lanes, disaggregated by the driver of biodiversity loss. **b,** Biodiversity footprint arising from local land use by traffic lanes in Finland. Footprints are expressed in nano biodiversity equivalents (nBDe).

## 4. Discussion

Our assessment shows that national transportation systems can generate biodiversity impacts not only through local infrastructure and traffic, but also through global value chains of fuels, vehicles and construction materials. In Finland, passenger car traffic and traffic lanes dominated both biodiversity and carbon footprints, while climate change was the major driver

of biodiversity loss across most subsystems of transportation system. These findings show that carbon accounting and local biodiversity assessment alone can miss a large share of the environmental burden of transportation systems.

Passenger car traffic was the largest contributor to the biodiversity and carbon footprints of traffic. This reflects the continued dominance of private cars in Finland's transportation system, particularly petrol cars, which remained the most common type of passenger car type during 2016-2023, with approximately 1.8–1.9 million registered vehicles (Statistics Finland, 2026c). High vehicle numbers and travel volumes therefore translated into large biodiversity and carbon footprints. Our finding that traffic-related biodiversity impacts were driven largely by climate change further demonstrates that transport contributes to biodiversity loss not only through local pressures, but also through greenhouse gas emissions that accumulate in the atmosphere and increase climate-mediated extinction risk (Román-Palacios and Wiens, 2020; Urban, 2024).

The magnitude of the value-chain burden is striking: the life cycle carbon footprint of the Finnish transportation system slightly exceeded Finland's total cumulative emissions during 2010–2024, including the LULUCF sector (Statistics Finland, 2026d). Although these estimates represent different accounting perspectives, the comparison shows that conventional territorial or local assessments can substantially understate the environmental burden of transport, vehicles and transport infrastructure. Life cycle biodiversity and climate impact assessment is therefore essential for evaluating the full consequences of national transportation systems.

Biofuels have been promoted in Europe and globally to reduce greenhouse gas emissions from transport (Directive (EU) 2018/2001; Jeswani et al., 2020). However, our findings suggest that a large-scale biodiesel introduction can increase the biodiversity footprint of passenger car

transport, even when carbon impacts decline. This is consistent with previous studies showing that first-generation biofuels (i.e. biofuels produced from food crops) can cause greater biodiversity loss than fossil fuels (Elshout et al., 2019), and that land-use changes associated with biofuel production have affected local species richness across the globe (Tudge, 2021). Moreover, the climate benefits of biofuels are uncertain and, in some cases, may be smaller than expected or even worse than those of fossil fuels (Carneiro et al., 2017; Jeswani et al., 2020; Lapola et al., 2010). The biodiversity and climate impacts of biofuels therefore depend strongly on the feedstock type, feedstock production location and fuel-conversion pathway (Carneiro et al., 2017; Jeswani et al., 2020; Tudge, 2021). Although second-generation biofuels (i.e. biofuels generated from non-food biomass and residues) are generally expected to have lower climate and biodiversity impacts than first-generation biofuels (Jeswani et al., 2020; Tudge, 2021), their impacts can also be significant, particularly if lower energy density of feedstock requirements increase land demand (Tudge, 2021).

Biodiesel had the largest biodiversity footprint per passenger kilometre of all passenger transport options assessed. This result reflects not only the motive power itself, but also broader differences in occupancy and transport efficiency. Public transport modes had substantially lower passenger-kilometre impacts than private cars, largely because they carry more passengers per vehicle. Our results therefore support earlier findings that walking, cycling and public transport can substantially reduce the environmental impacts of mobility (Baumeister, 2019; Brand et al., 2021; Ercan et al., 2016), while also offering potential synergies between biodiversity, climate and health (IPBES, 2024; Perilli et al., 2025).

Traffic lanes were the other major contributor to the biodiversity and carbon footprints of the Finnish transportation system. While it is well known that roads cause destruction and fragmentation, and that surrounding areas are affected by pollution, noise, and other traffic-related pressures that reduce habitat quality (Coffin, 2007; Karlson and Mörtberg, 2015;

Trombulak and Frissell, 2000; van Strien and Grêt-Regamey, 2025), our results add a life cycle perspective with a striking result: the biodiversity footprint of traffic lanes far exceed their local land-use footprint. In other words, the materials and energy used to build roads in national transportation systems can contribute substantially to global biodiversity loss and even more than the local land use change caused by road construction.

This finding aligns with previous studies showing that road construction, operation and maintenance require large material and energy inputs (Chester and Horvath, 2009; Santos et al., 2015), and that upstream material production contributes to energy use, pollution and greenhouse gas emissions (Chester and Horvath, 2009; Hanson and Noland, 2015; Santos et al., 2015). Finland's road networks is approximately 454,000 km long (Finnish Transport Infrastructure Agency, 2026) and therefore represents both a direct land use pressure and a substantial value chain burden. Globally, with more than 21 million km of roads (Meijer et al., 2018), such displaced impacts may be an important but under-recognized component of transport-related biodiversity loss.

### 4.3. Limitations

Several limitations should be considered. We could not include use-phase effects of roads such as leachate production and rolling resistance (Araújo et al., 2014; Yang et al., 2015), nor habitat fragmentation, although fragmentation and disturbances caused by road network contribute substantially to global terrestrial biodiversity loss (Wilting et al., 2017). Including these effects would likely increase the estimated local biodiversity footprint of traffic lanes.

Some transportation system components also lacked adequate data or characterization factors needed to operate the BIOVALENT method (see Fig. D.1). Biofuel impacts were particularly uncertain because Finnish fuel consumption statistics do not distinguish pure from blended biofuels or specify feedstock composition (Statistics Finland, 2025b). Consequently, greater

transparency from biofuel producers and retailers is needed to assess whether biofuels deliver genuine climate and biodiversity benefits or shift impacts elsewhere. Our assessment may underestimate land use impacts of biofuels, as there are no data on how much the consumption of biofuels in Finland drives land use change and we could not consider possible indirect land use caused by biofuel production (Ahlgren and Di Lucia, 2014; Jeswani et al., 2020).

#### 4.2. Towards transportation systems embracing the nature-climate nexus

Despite its limitations, our assessment shows that national transportation systems can be substantial and multifaceted drivers of biodiversity loss. Their impacts arise not only locally, through land use and traffic, but also globally through the value chains of vehicles, fuels and construction materials and activities for infrastructure (Lenzen et al., 2012; Verones et al., 2017; Wilting et al., 2017). This makes transportation a central arena for addressing the nature-climate nexus: climate and biodiversity impacts are strongly connected, but mitigation actions do not always benefit both.

Our results show why climate and biodiversity impacts must be assessed together. Electrification of passenger cars can substantially reduce both carbon and biodiversity footprints when powered by low-impact electricity (Jaramillo et al., 2022; Jenu et al., 2021), even though electric vehicle production requires more materials and energy than conventional vehicles (Hawkins et al., 2013; Watari et al., 2019). These upstream impacts can be reduced through efficient battery recycling (Faria et al., 2013; Lai et al., 2022; Nordelöf et al., 2014), moderate vehicle size (Ellingsen et al., 2016; Faria et al., 2013; Nordelöf et al., 2014), and environmentally sustainable electricity production (Faria et al., 2013; Hawkins et al., 2013; Jenu et al., 2021). Also, biogas may provide benefits in some contexts, but its biodiversity and climate outcome depend strongly on feedstocks used (Hijazi et al., 2016; Noussan et al., 2024). Climate-oriented transport policy can therefore create biodiversity trade-offs if value-chain impacts are ignored (Pörtner et al., 2021; Santangeli et al., 2016a; Shin, 2022).

Infrastructure mitigation also requires a life-cycle perspective. Reducing material demand, improving energy efficiency, using recycled materials and selecting lower-impact construction materials can reduce greenhouse gas related biodiversity impacts from transport infrastructure (Araújo et al., 2014; Wilting and van Oorschot, 2017; Yang et al., 2015). However, technological substitution alone is unlikely to be sufficient. Because consumption is a major driver of biodiversity loss (Díaz et al., 2019; Lenzen et al., 2012), the strongest and most consistent synergies are likely to come from reducing transport demand and shifting mobility from private cars towards walking, cycling and public transport (Brand et al., 2021; Chester and Horvath, 2009; Cuenot et al., 2012). Such shifts can reduce carbon emissions, biodiversity pressures and infrastructure land requirements, while also supporting health benefits (Perilli et al., 2025).

National transport policy is therefore also policy on global biodiversity spillovers. Decisions made within national transport systems can displace biodiversity impacts through the international value chains of fuels, vehicles and infrastructure, beyond the reach of territorial emissions accounting or local impact assessment. Meeting the goals of the Kunming–Montreal Global Biodiversity Framework and the Paris Agreement will require national transport policies that recognize these spillovers and reduce them through integrated life-cycle assessment of biodiversity and climate impacts. Recognizing and reducing these spillovers should become a core objective of national transport policy.

## 5. Conclusions

Transportation systems generate local biodiversity impacts and substantial amounts of greenhouse gas emissions. Yet, the biodiversity impacts arising from value chains of vehicles, fuel production and transport infrastructure construction remain largely unknown. Using the BIOVALENT method, we assessed the biodiversity and carbon footprints of the Finnish

transportation system. The transportation system generated a biodiversity footprint of 1,152,207 nano biodiversity equivalents (nBDe), corresponding to an estimated potential extinction risk for approximately 0.1% of global species, and a carbon footprint of 677 Mt CO<sub>2</sub>e. Passenger car traffic and traffic lanes accounted for the largest biodiversity and carbon footprints. Climate change was the largest driver of biodiversity loss across most transportation sub-systems, while some decarbonisation measures of transport, such as biofuel adoption, can create trade-offs for biodiversity. Comparison of the local land use biodiversity impacts of transport lanes to those arising from their value chains demonstrated that transportation systems can generate substantial biodiversity impacts outside national borders. These findings emphasize that simultaneous biodiversity and carbon footprint assessment should be integrated into transport policy to avoid overlooking biodiversity trade-offs and global biodiversity spillovers embedded in international value-chains.

## CRedit Authorship contribution statement

**Venla Leppilampi:** Writing – original draft, Conceptualization, Data curation, Investigation, Methodology, Visualisation. **Janne S. Kotiaho:** Writing – review and editing, Conceptualization, Methodology, Supervision. **Stefan Baumeister:** Writing – review and editing, Conceptualization, Methodology, Supervision. **Essi Järvinen:** Data curation. **Sami El Geneidy:** Writing – review and editing, Conceptualization, Methodology, Supervision.

## Declaration of competing interests

The authors declare no competing interests.

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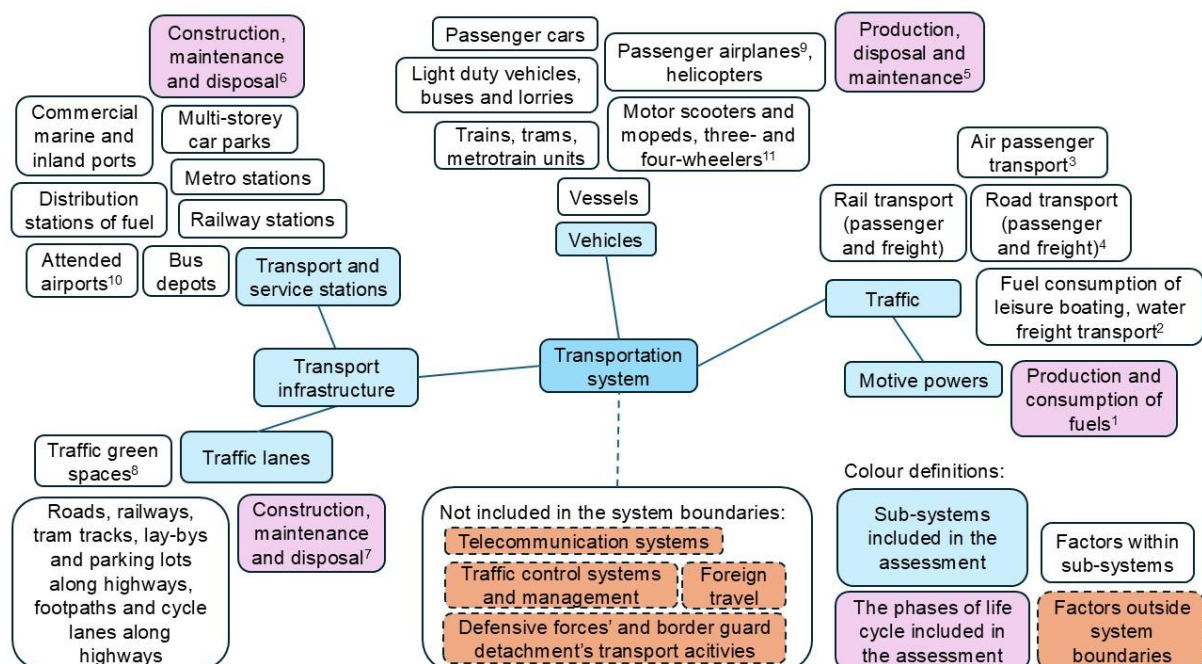
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## Appendix A. Supplementary Information

Supplementary Information is available at Zenodo: <https://doi.org/10.5281/zenodo.23101061>

(Supplementary Methods, Supplementary Tables 1-3 and Supplementary References)

## Appendix B. Detailed description of system boundaries



**Fig. B.1: Mind map of the system boundaries for the assessment of biodiversity and climate impact of the Finnish transportation system. 1) Fuel consumption in transportation**

is included within the impacts of traffic. 2) The biodiversity and climate impacts of water-based passenger transport could not be assessed. No corresponding process exists ecoinvent v.3.10.1 and to our knowledge, no studies provide characterization factors that could be utilised in the BIOVALENT method. 3) To avoid double counting, the biodiversity impact was assessed only for air passenger transport, as freight is also carried on passenger flights. Helicopter traffic was left out due to absence of national data. 4) Cycling was left out, because there is no national data on the passenger-kilometres travelled of cycling. Electric scooter traffic was left out due to lack of data of characterization factors. 5) The life cycle impacts of vehicles do not include aircraft maintenance or the disposal of good wagons and helicopters. 6) Maintenance of fuel distribution stations is not included. 7) Maintenance of tram tracks and lay-bys is not included. Roads also cover tunnel and bridge structures. 8) Green spaces along highways and cycleways and walkways are included. 9) Other aircraft types, such as light aircrafts, could not be included due to lack of suitable characterization factors. 10) “Attended airports” refer to airports with regular transport and are operated by Finavia, the Finnish airport company. 11) Bicycles were excluded because no national data exist on the total number of bicycles in Finland.

## Appendix C. Additional results

**Table C.1: The share of the biodiversity and carbon footprints of the factors within the subsystems of the Finnish transportation system, shown as proportions of each subsystem’s impacts and of the total biodiversity and carbon footprints of the Finnish transportation system.** P. cars refers to passenger cars. The impacts of electric passenger cars and plug-in hybrids include battery. In hybrids, (p) denotes plug-in hybrids using electricity and petrol, and (d) denotes plug-in hybrids using electricity and diesel as a motive power.

| Factors within sub-systems of Finnish | Share of sub-system’s | Share of sub-system’s | Share of total biodiversity | Share of total carbon |
|---------------------------------------|-----------------------|-----------------------|-----------------------------|-----------------------|
|---------------------------------------|-----------------------|-----------------------|-----------------------------|-----------------------|

| transportation<br>system                                   | biodiversity<br>footprint<br>(%) | carbon<br>footprint<br>(%) | footprint<br>(%) | footprint<br>(%) |
|------------------------------------------------------------|----------------------------------|----------------------------|------------------|------------------|
| <hr/> Production of<br>vehicles <hr/>                      |                                  |                            |                  |                  |
| Vans                                                       | 5.3                              | 4.8                        | 0.6              | 0.5              |
| Buses                                                      | 1.0                              | 1.0                        | 0.1              | 0.1              |
| Lorries                                                    | 5.4                              | 5.5                        | 0.6              | 0.6              |
| Diesel p. cars                                             | 13.5                             | 13.9                       | 1.5              | 1.5              |
| Petrol p. cars                                             | 37.5                             | 38.4                       | 4.1              | 4.1              |
| Natural gas p. cars                                        | 0.1                              | 0.1                        | 0.0              | 0.0              |
| Electric p. cars                                           | 1.7                              | 1.6                        | 0.2              | 0.2              |
| Hybrid p. cars (p)                                         | 2.5                              | 2.5                        | 0.3              | 0.3              |
| Hybrid p. cars (d)                                         | 0.1                              | 0.1                        | 0.0              | 0.0              |
| P. cars with other<br>motive power                         | 0.0                              | 0.0                        | 0.0              | 0.0              |
| Motor scooters                                             | 0.2                              | 0.2                        | 0.0              | 0.0              |
| Mopeds                                                     | 0.2                              | 0.2                        | 0.0              | 0.0              |
| Three- and four-<br>wheelers                               | 0.0                              | 0.0                        | 0.0              | 0.0              |
| Trams                                                      | 0.0                              | 0.0                        | 0.0              | 0.0              |
| Locomotives and<br>steam locomotives                       | 0.5                              | 0.4                        | 0.1              | 0.0              |
| Wagons (freight)                                           | 0.9                              | 0.9                        | 0.1              | 0.1              |
| Wagons<br>(passenger)                                      | 0.1                              | 0.1                        | 0.0              | 0.0              |
| Motor train unit<br>(long distance)                        | 0.3                              | 0.3                        | 0.0              | 0.0              |
| Motor train unit<br>(regional)                             | 0.1                              | 0.1                        | 0.0              | 0.0              |
| Metrotrain units                                           | 0.0                              | 0.0                        | 0.0              | 0.0              |
| Barges and other<br>engineless ships                       | 0.4                              | 0.4                        | 0.0              | 0.0              |
| Bulk carriers for<br>dry goods                             | 9.9                              | 9.7                        | 1.1              | 1.0              |
| Passenger ships                                            | 4.6                              | 4.5                        | 0.5              | 0.5              |
| Tankers                                                    | 0.7                              | 0.7                        | 0.1              | 0.1              |
| Special purpose<br>vessels                                 | 9.0                              | 8.8                        | 1.0              | 0.9              |
| Other vessels                                              | 5.2                              | 5.0                        | 0.6              | 0.5              |
| Helicopters                                                | 0.0                              | 0.0                        | 0.0              | 0.0              |
| Short, medium and<br>long-haul belly-<br>freight aircrafts | 0.6                              | 0.6                        | 0.1              | 0.1              |
| <hr/> Maintenance of<br>vehicles <hr/>                     |                                  |                            |                  |                  |
| Vans                                                       | 10.0                             | 8.8                        | 0.1              | 0.1              |
| Buses                                                      | 2.3                              | 2.2                        | 0.0              | 0.0              |
| Lorries                                                    | 13.8                             | 14.1                       | 0.2              | 0.2              |

|                                      |      |      |      |      |
|--------------------------------------|------|------|------|------|
| Diesel p. cars                       | 10.1 | 9.9  | 0.1  | 0.1  |
| Petrol p. cars                       | 28.3 | 28.2 | 0.4  | 0.4  |
| Natural gas p. cars                  | 0.1  | 0.1  | 0.0  | 0.0  |
| Electric p. cars                     | 0.6  | 0.6  | 0.0  | 0.0  |
| Hybrid p. cars (p)                   | 1.5  | 1.5  | 0.0  | 0.0  |
| Hybrid p. cars (d)                   | 0.1  | 0.1  | 0.0  | 0.0  |
| P. cars with other<br>motive power   | 0.0  | 0.0  | 0.0  | 0.0  |
| Motor scooters                       | 0.8  | 0.8  | 0.0  | 0.0  |
| Mopeds                               | 1.0  | 1.0  | 0.0  | 0.0  |
| Three- and four-<br>wheelers         | 0.1  | 0.1  | 0.0  | 0.0  |
| Trams                                | 0.0  | 0.0  | 0.0  | 0.0  |
| Locomotives and<br>steam locomotives | 0.8  | 0.8  | 0.0  | 0.0  |
| Wagons (freight)                     | 4.0  | 4.1  | 0.1  | 0.1  |
| Wagons<br>(passenger)                | 0.3  | 4.1  | 0.0  | 0.1  |
| Motor train unit<br>(long-distance)  | 0.1  | 0.1  | 0.0  | 0.0  |
| Motor train unit<br>(regional)       | 0.8  | 0.8  | 0.0  | 0.0  |
| Metro train units                    | 0.0  | 0.0  | 0.0  | 0.0  |
| Barges and other<br>engineless ships | 0.8  | 0.7  | 0.0  | 0.0  |
| Bulk carriers for<br>dry goods       | 8.1  | 7.3  | 0.1  | 0.1  |
| Passenger ships                      | 3.8  | 3.4  | 0.1  | 0.0  |
| Tankers                              | 0.6  | 0.5  | 0.0  | 0.0  |
| Special purpose<br>vessels           | 7.5  | 6.7  | 0.1  | 0.1  |
| Other vessels                        | 4.3  | 3.9  | 0.1  | 0.1  |
| <hr/>                                |      |      |      |      |
| Traffic                              |      |      |      |      |
| Electric p. cars                     | 0.0  | 0.0  | 0.0  | 0.0  |
| Diesel p. cars,<br>fossil diesel     | 11.8 | 11.9 | 5.5  | 6.2  |
| Diesel p. cars,<br>biodiesel         | 1.2  | 1.1  | 0.6  | 0.6  |
| Petrol p. cars                       | 47.4 | 48.4 | 22.2 | 25.4 |
| Flexfuel (E85) p.<br>cars            | 0.0  | 0.0  | 0.0  | 0.0  |
| Gas p. cars, natural<br>gas          | 0.1  | 0.1  | 0.0  | 0.0  |
| Gas p. cars, biogas                  | 0.0  | 0.0  | 0.0  | 0.0  |
| Hybrid p. cars (p)                   | 0.6  | 0.6  | 0.3  | 0.3  |
| Hybrid p. cars (d)                   | 0.0  | 0.0  | 0.0  | 0.0  |
| P. cars with other<br>motive power   | 0.0  | 0.0  | 0.0  | 0.0  |

|                                                                       |      |      |     |     |
|-----------------------------------------------------------------------|------|------|-----|-----|
| Petrol/gas (biogas)<br>p. cars                                        | 0.1  | 0.1  | 0.0 | 0.0 |
| Buses                                                                 | 5.1  | 4.8  | 2.4 | 2.5 |
| Motor scooters,<br>mopeds, three- and<br>four-wheelers                | 0.8  | 0.8  | 0.4 | 0.4 |
| Haulage driven by<br>vans                                             | 12.2 | 12.2 | 5.7 | 6.4 |
| Lorries (weight<br>3500 - 7500<br>tonnes)                             | 0.2  | 0.2  | 0.1 | 0.1 |
| Lorries (weight<br>7500 - 16 000<br>tonnes)                           | 0.5  | 0.5  | 0.2 | 0.3 |
| Lorries (weight<br>16 000 - 32 000<br>tonnes)                         | 2.0  | 2.0  | 1.0 | 1.1 |
| Lorries (weight<br>16 000 - 32 000<br>tonnes), biodiesel              | 0.3  | 0.2  | 0.1 | 0.1 |
| Lorries (weight<br>more than 32 000<br>tonnes)                        | 12.0 | 12.0 | 5.6 | 6.3 |
| Train passenger<br>transport (long-<br>distance and<br>regional)      | 0.1  | 0.1  | 0.1 | 0.1 |
| Metro passenger<br>transport                                          | 0.1  | 0.1  | 0.0 | 0.0 |
| Tramway<br>passenger transport                                        | 0.0  | 0.0  | 0.0 | 0.0 |
| Freight transport,<br>electric train                                  | 0.5  | 0.5  | 0.2 | 0.2 |
| Freight transport,<br>diesel train                                    | 0.9  | 0.8  | 0.4 | 0.4 |
| Air passenger<br>transport                                            | 1.3  | 1.2  | 0.6 | 0.6 |
| Vessel freight<br>transport, inland<br>waterways                      | 0.0  | 0.1  | 0.0 | 0.0 |
| Vessel freight<br>transport on coastal<br>waterways, bulk<br>carriers | 0.4  | 0.2  | 0.2 | 0.1 |
| Vessel freight<br>transport on coastal<br>waterways, tankers          | 0.1  | 0.0  | 0.0 | 0.0 |
| Log floating                                                          | 0.1  | 0.1  | 0.0 | 0.1 |
| Dredging masses<br>haulage                                            | 0.0  | 0.0  | 0.0 | 0.0 |

|                                                         |      |      |      |      |
|---------------------------------------------------------|------|------|------|------|
| Leisure boating – petrol consumption                    | 2.0  | 2.0  | 0.9  | 1.1  |
| Leisure boating – diesel consumption                    | 0.4  | 0.0  | 0.2  | 0.0  |
| Transport infrastructure                                |      |      |      |      |
| Highways                                                | 17.7 | 18.6 | 6.8  | 6.6  |
| Footpaths and cycle lanes along highways                | 1.4  | 1.5  | 0.5  | 0.5  |
| Street network of municipalities                        | 5.9  | 6.2  | 2.3  | 2.2  |
| Private and forest roads                                | 43.9 | 45.1 | 17.0 | 16.0 |
| Railroads                                               | 7.0  | 7.4  | 2.7  | 2.6  |
| Tram tracks                                             | 0.2  | 0.2  | 0.1  | 0.1  |
| Metro tracks                                            | 0.1  | 0.1  | 0.0  | 0.0  |
| Lay-bys                                                 | 0.0  | 0.0  | 0.0  | 0.0  |
| Parking lots                                            | 0.2  | 0.2  | 0.1  | 0.1  |
| Distribution stations of liquid fuels                   | 9.1  | 6.2  | 3.5  | 2.2  |
| Distribution stations of gas                            | 0.0  | 0.0  | 0.0  | 0.0  |
| Commercial sea and inland ports in Finland              | 9.5  | 9.7  | 3.7  | 3.4  |
| Airports                                                | 2.6  | 2.8  | 1.0  | 1.0  |
| Railway stations                                        | 0.4  | 0.3  | 0.1  | 0.1  |
| Bus depots                                              | 0.1  | 0.1  | 0.0  | 0.1  |
| Multi-storey car parks                                  | 1.6  | 1.4  | 0.6  | 0.5  |
| Metro stations                                          | 0.2  | 0.2  | 0.1  | 0.1  |
| Maintenance of highways                                 | 3.9  | 0.0  | 1.6  | 0.0  |
| Maintenance of footpaths and cycle lanes along highways | 0.31 | 0.0  | 0.1  | 0.0  |
| Maintenance of street network of municipalities         | 1.31 | 0.0  | 0.5  | 0.0  |

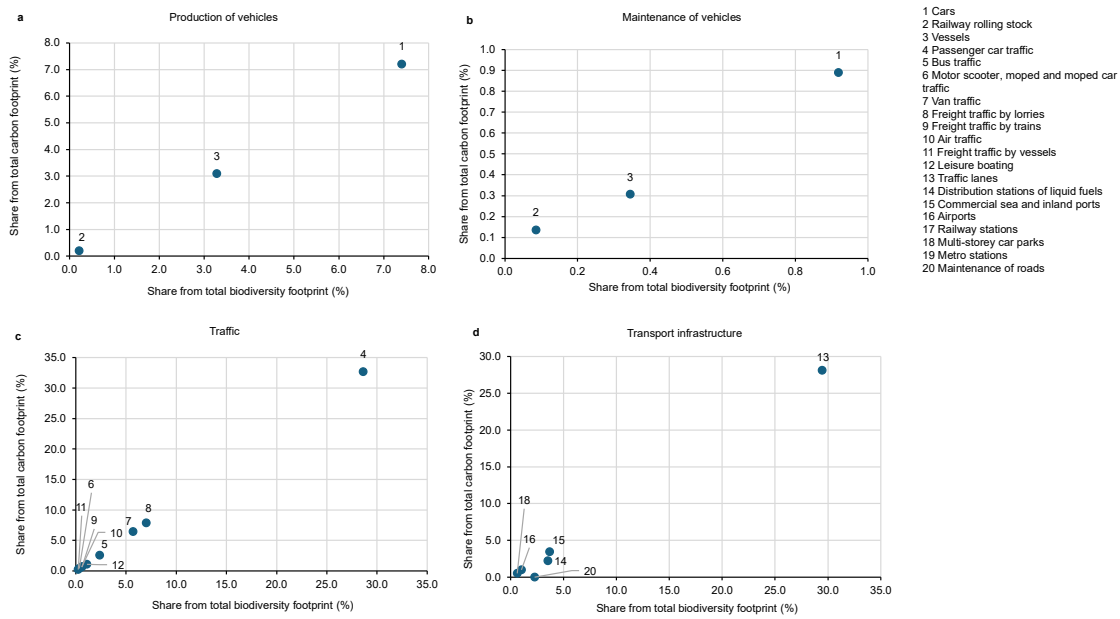
**Table C.2: Distribution of the biodiversity impact of the drivers of biodiversity loss in terrestrial and freshwater ecosystems of factors within each subsystem of Finnish transportation system.**

| Factors within sub-system                        | Terrestrial ecosystems |           |                | Freshwater ecosystems |                |                 |
|--------------------------------------------------|------------------------|-----------|----------------|-----------------------|----------------|-----------------|
|                                                  | Land use               | Pollution | Climate change | Pollution             | Climate change | Water depletion |
| <b>Production, vehicles</b>                      |                        |           |                |                       |                |                 |
| Passenger cars                                   | 2 %                    | 7 %       | 91 %           | 19 %                  | 29 %           | 52 %            |
| Vans                                             | 4 %                    | 14 %      | 82 %           | 33 %                  | 22 %           | 45 %            |
| Buses                                            | 3 %                    | 9 %       | 88 %           | 23 %                  | 31 %           | 46 %            |
| Lorries                                          | 2 %                    | 8 %       | 89 %           | 26 %                  | 33 %           | 41 %            |
| Motor scooters, mopeds, three- and four-wheelers | 2 %                    | 9 %       | 89 %           | 20 %                  | 31 %           | 48 %            |
| Railway rolling stock                            | 5 %                    | 10 %      | 84 %           | 26 %                  | 27 %           | 46 %            |
| Vessels                                          | 5 %                    | 7 %       | 88 %           | 18 %                  | 25 %           | 57 %            |
| Aircrafts                                        | 3 %                    | 14 %      | 83 %           | 14 %                  | 43 %           | 43 %            |
| Helicopters                                      | 1 %                    | 8 %       | 90 %           | 20 %                  | 37 %           | 43 %            |
| <b>Maintenance, vehicles</b>                     |                        |           |                |                       |                |                 |
| Passenger cars                                   | 4 %                    | 8 %       | 89 %           | 11 %                  | 37 %           | 52 %            |
| Vans                                             | 15 %                   | 7 %       | 78 %           | 14 %                  | 32 %           | 54 %            |
| Buses                                            | 17 %                   | 3 %       | 81 %           | 15 %                  | 52 %           | 33 %            |
| Lorries                                          | 5 %                    | 10 %      | 85 %           | 13 %                  | 29 %           | 58 %            |

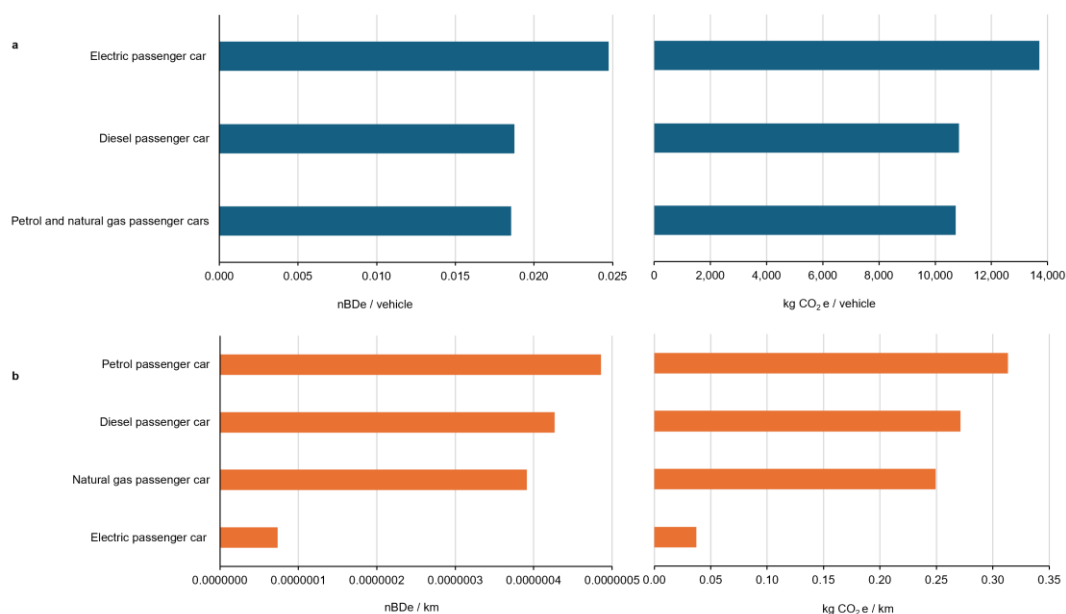
|                                                  |     |      |      |       |       |      |
|--------------------------------------------------|-----|------|------|-------|-------|------|
| Motor scooters, mopeds, three- and four-wheelers | 3 % | 8 %  | 90 % | 10 %  | 34 %  | 57 % |
| Railway rolling stock                            | 4 % | 8 %  | 88 % | 24 %  | 43 %  | 33 % |
| Vessels                                          | 9 % | 8 %  | 82 % | 14 %  | 27 %  | 60 % |
| <u>Traffic</u>                                   |     |      |      |       |       |      |
| Passenger car                                    | 0 % | 2 %  | 98 % | 0.5 % | 99 %  | 1 %  |
| Van                                              | 0 % | 3 %  | 97 % | 2 %   | 98 %  | 0 %  |
| Bus                                              | 0 % | 9 %  | 91 % | 0 %   | 100 % | 0 %  |
| Lorry                                            | 0 % | 4 %  | 96 % | 1 %   | 98 %  | 0 %  |
| Motor scooter, moped, three- and four-wheeler    | 0 % | 4 %  | 96 % | 1 %   | 99 %  | 0 %  |
| Railway, passenger                               | 1 % | 2 %  | 97 % | 27 %  | 68 %  | 5 %  |
| Railway, freight                                 | 0 % | 10 % | 89 % | 10 %  | 90 %  | 0 %  |
| Vessel                                           | 0 % | 31 % | 69 % | 16 %  | 84 %  | 0 %  |
| Air, passenger                                   | 0 % | 10 % | 90 % | 1 %   | 99 %  | 0 %  |
| Leisure boating                                  | 0 % | 2 %  | 98 % | 2 %   | 98 %  | 0 %  |
| <u>Transport infrastructure</u>                  |     |      |      |       |       |      |
| Roads                                            | 4 % | 14 % | 82 % | 5 %   | 75 %  | 20 % |
| Train, tram and metro tracks                     | 4 % | 8 %  | 88 % | 16 %  | 43 %  | 41 % |

|                                                 |      |      |      |      |      |      |
|-------------------------------------------------|------|------|------|------|------|------|
| Lay-bys and parking lots along highways         | 1 %  | 10 % | 89 % | 8 %  | 58 % | 34 % |
| Distribution stations of fuels (liquid and gas) | 36 % | 10 % | 54 % | 22 % | 22 % | 57 % |
| Commercial sea and inland ports                 | 5 %  | 14 % | 81 % | 8 %  | 74 % | 18 % |
| Airports                                        | 10 % | 5 %  | 85 % | 21 % | 57 % | 23 % |
| Railway stations                                | 13 % | 10 % | 77 % | 14 % | 39 % | 47 % |
| Bus depots                                      | 5 %  | 10 % | 85 % | 14 % | 39 % | 47 % |
| Multi-storey car parks                          | 11 % | 18 % | 71 % | 43 % | 20 % | 37 % |
| Metro stations                                  | 3 %  | 11 % | 86 % | 30 % | 49 % | 20 % |
| Maintenance of roads                            | 23 % | 4 %  | 73 % | 18 % | 38 % | 44 % |

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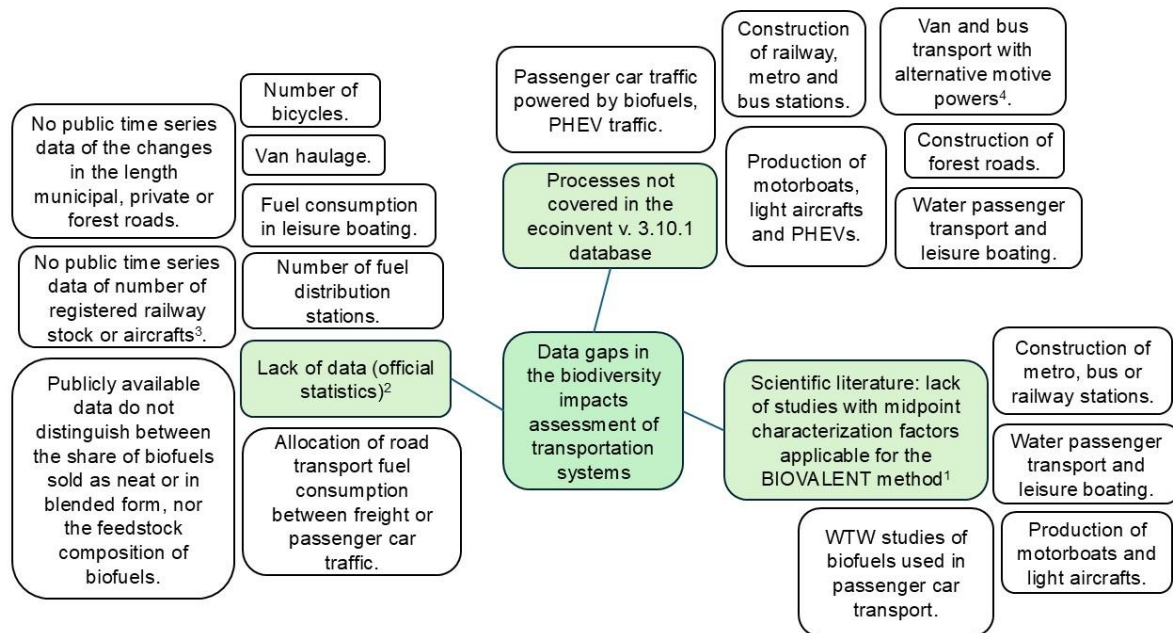


**Fig. C.1: Share of the total carbon footprint in relation to the share of the total biodiversity footprint for factors within each sub-system (a-b).** In panel c, both points 9 and 10 have value 0.6 on the x-axis and 0.7 on the y-axis. Please note that the horizontal and vertical axis scales differ between panels, depending on the relative share of total footprints. Factors for which both values are below 0.1 are omitted for clarity.



**Fig. C.2: Life cycle impacts of passenger car production and use. a,** Biodiversity and carbon footprints of electric, diesel, petrol and natural gas passenger cars per one produced vehicle. **b,** Biodiversity and carbon footprints of electric, diesel, petrol and natural gas passenger cars per one kilometre driven. Since the impacts per one kilometre driven (**b**) represent the full life cycle impacts, the modelling also includes vehicle production, road construction and maintenance. Please note that the axes are presented on an order of magnitude scale. The impacts of traffic correspond to medium sized vehicles in Euro class 4. The life cycle impacts of electric passenger car production include battery production, assuming a battery weight of 500 kg. The energy use for driving the electric passenger car is based on Finnish electricity mix in 2023.

## Appendix D. Data gaps in the biodiversity impact assessment of transportation systems



**Fig. D.1: Data gaps in the biodiversity impact assessment of transportation systems,**

**classified into database, literature and data availability categories.** WTW refers to well-to-wheels analysis, in which the life cycle impacts of fuel production, transportation and use is considered. PHEV refers to plug-in hybrid electric vehicles. Some of the data gaps fall into both databases and literature related categories. 1) Midpoint characterization factors applicable in the BIOVALENT method refer to factors that address the same drivers of biodiversity loss and use the same unit as in BIOVALENT method. In terms of transport, characterization factors should be derived from a well-to-wheels analysis in which impacts are modelled for driving a medium-sized passenger car, to align with the research frame in our study. 2) Refers to the lack of case (Finland) specific assessment data. Due to lack of official statistics, we relied on estimates or unofficial information, which increases the uncertainty of the assessment. 3) Only the most recent updated data are available in public

registers, rather than full time-series data. 4) Electric bus transport is included in the ecoinvent v.3.10.1 database, but transport operated on biofuels is not covered.

## Data availability

The datasets used and created in this paper are available at Zenodo:

<https://doi.org/10.5281/zenodo.23101061>

## Code availability

The code used in this paper is available in Zenodo: <https://doi.org/10.5281/zenodo.22008734>

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