Global biodiversity impact spillovers of national transportation systems

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Summary paragraph

Transportation systems cause well-documented local biodiversity impacts and substantial greenhouse gas emissions[1–8,28], yet the global biodiversity impacts embedded in their value chains remain poorly understood. Here, we quantify the life cycle biodiversity and carbon footprints of Finland's national transportation system, covering traffic, transport infrastructure, and vehicle production and maintenance, using detailed national data and the Biodiversity Equivalent Impact Assessment method (BIOVALENT)[36]. The transportation system generated a biodiversity footprint corresponding to an estimated potential extinction risk for approximately 0.1 percent of global species, and a carbon footprint of 677 megatons of carbon dioxide equivalents. Passenger car traffic and traffic lanes were the largest contributors to both footprints, and climate change was the dominant driver of biodiversity loss across most system components. Notably, for traffic lanes, life cycle biodiversity impacts were approximately 45 times larger than impacts from local land-use change alone, demonstrating substantial global biodiversity spillovers from national transport infrastructure. Scenario analysis showed that passenger car electrification can substantially reduce both biodiversity and carbon footprints, whereas biofuel adoption may reduce carbon impacts while increasing biodiversity loss. These findings highlight the need for transport policy to integrate life cycle biodiversity and climate impact assessment to avoid overlooking global impacts and unintended biodiversity-climate trade-offs.

Main

Transportation systems have well-established local impacts on biodiversity and make substantial contributions to greenhouse gas emissions[1–8,28]. 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[9,10]. 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[11], driven by land- and sea-use change, direct exploitation of organisms, climate change, pollution and invasive alien species[12]. Among these drivers, climate change is becoming increasingly important[13,14], largely as a result of anthropogenic greenhouse gas emissions[15,16], to which transport is a major and growing contributor[17,18]. Despite international commitments to mitigate climate change and halt biodiversity loss, neither global emissions nor biodiversity decline shows clear signs of slowing[11,19]. 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[20,21]. Yet transport policy and assessment remain dominated by climate metrics[22–27], 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[1,9,10,28,29], 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[30,31], 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.

To address these questions, we compiled national activity data on traffic, including annual data for 2016-2023, together with data on transport infrastructure and vehicle production and maintenance. We assessed biodiversity and carbon footprints using the Biodiversity Equivalent Impact Assessment method, BIOVALENT[32], which builds on established life cycle assessment approaches[33,34]. Biodiversity impacts from land-use change, water depletion, pollution and climate change were assessed across terrestrial, freshwater and marine ecosystems[32] and expressed as biodiversity equivalents (BDe), a spatially explicit indicator of potential global species loss based on the potentially disappeared fraction of species[35,36]. Carbon footprints were expressed as carbon dioxide equivalents (CO_2e). The subsystems of the Finnish transportation system included were vehicle production and maintenance, domestic passenger and freight traffic and transport infrastructure.

Results

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_2e. 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% (Extended Data Table 1). Transport infrastructure was the second largest contributor, with traffic lanes alone accounting for 29 % of the total biodiversity footprint (Fig. 1a,b and Extended Data Table 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 (Extended Data Table 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 (Extended Data Fig. 2). Transport infrastructure was the second largest contributor, with traffic lanes alone accounting for approximately 28 % of the total carbon footprint (Extended Data Fig. 2). 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 (Extended Data Table 1 and Extended Data Fig. 2).

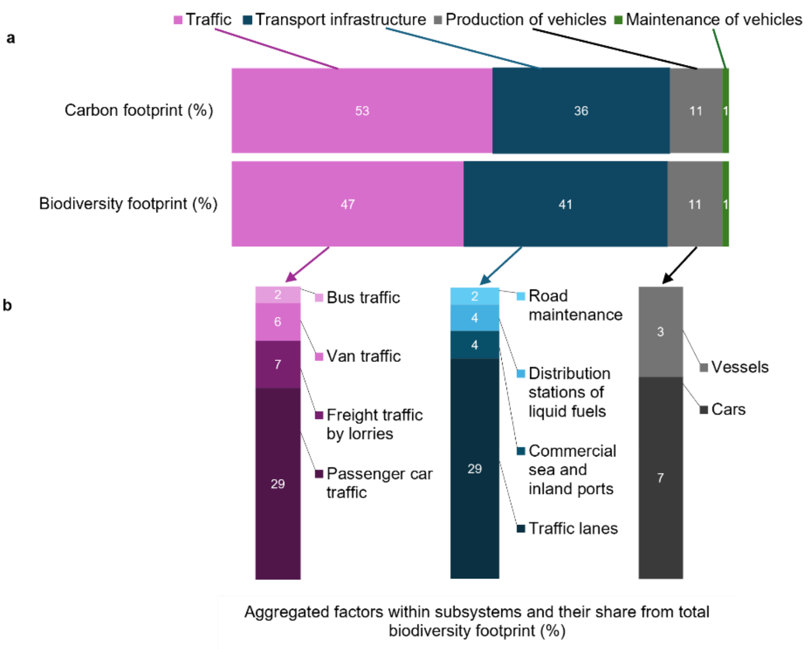

Fig. 1: Biodiversity and carbon footprints of the Finnish transportation system. a, Shares of the main subsystems in the total biodiversity and carbon footprints. **b)** Key contributors

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.

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).

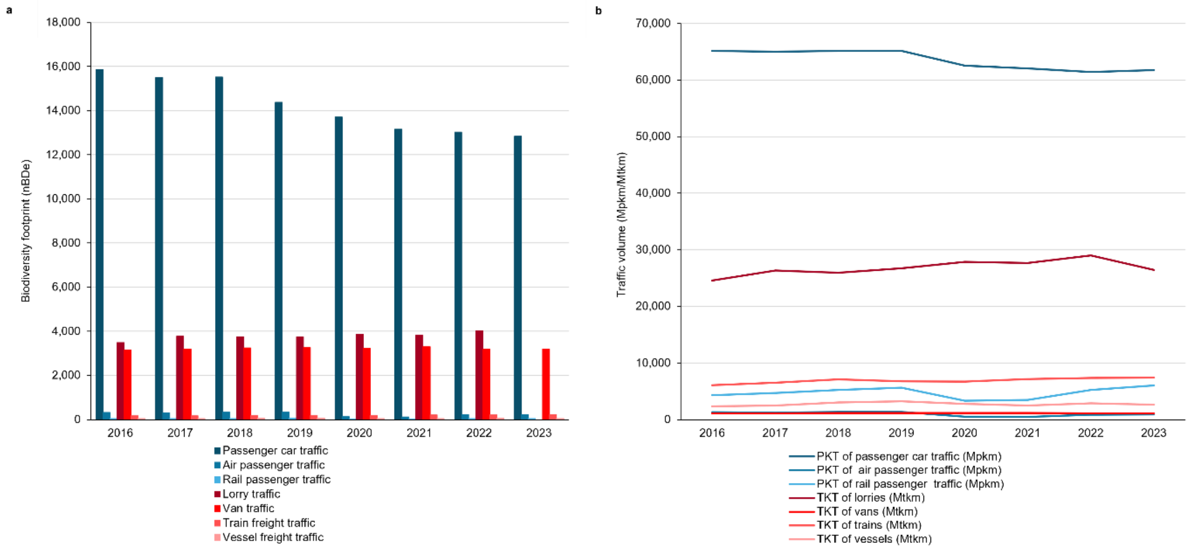

Fig. 2: Biodiversity footprint and traffic development of passenger and freight transport, 2016–2023. a, Biodiversity footprint of passenger and freight transport. **b,** Development of passenger and freight transport volumes. PKT denotes passenger-kilometres travelled and TKT tonne-kilometres travelled.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

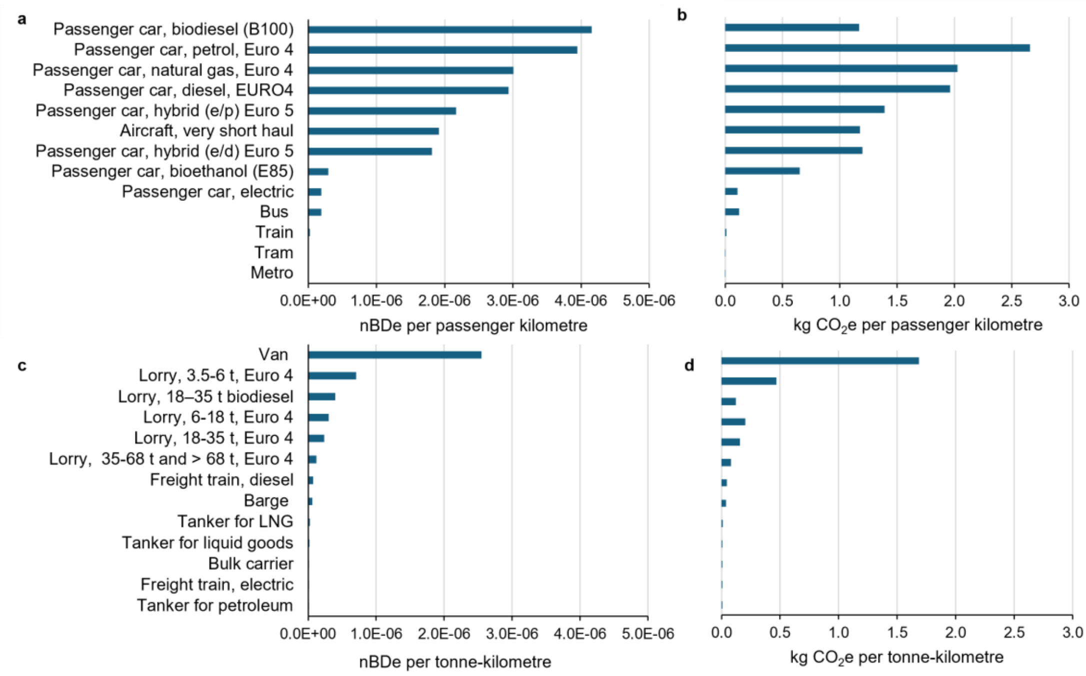

Fig. 3: Biodiversity and carbon intensities of passenger and freight modes in 2023. a, Biodiversity footprint intensity by vehicle type in passenger transport, expressed per passenger-kilometre. **b,** Carbon footprint intensity by vehicle type in passenger transport, expressed per passenger-kilometre. 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.

Climate change is the dominant 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 Extended Data Table 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 %

Electrification reduces both biodiversity and carbon footprints, whereas biodiesel creates biodiversity trade-offs

We used counterfactual scenarios to assess how alternative passenger car motive powers would have affected biodiversity and carbon footprints during 2016 – 2023. Realized footprints were compared with four scenarios based on realized vehicle-kilometres travelled: fossil fuel-only, where car fleet used fossil petrol and diesel, electricity-only, biodiesel-only, and electricity-biodiesel scenario in which diesel passenger cars used pure biodiesel and the rest of the passenger-car fleet was electric.

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 (Extended Data Fig. 3a, 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.

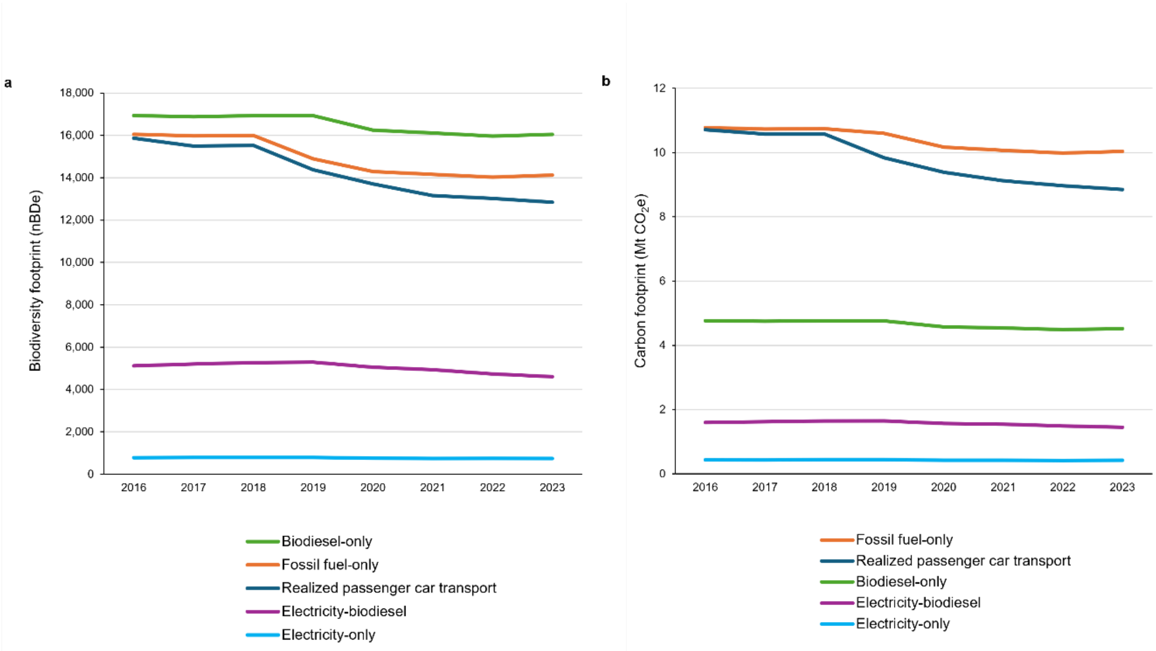

Fig. 4: Biodiversity and carbon footprints of passenger car motive power scenarios, 2016–2023. Scenario analysis comparing realized passenger-car traffic with fossil-fuel-only, electric-only, biodiesel-only and electric-biodiesel scenarios, using realized vehicle-kilometres travelled**. a,** Biodiversity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

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

To estimate the magnitude of global spillover impacts from transport infrastructure, we compared the life cycle biodiversity footprint of traffic lanes in Finland with the biodiversity footprint arising from their local land use. 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 traffic lanes in Finland (Fig. 5).

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.

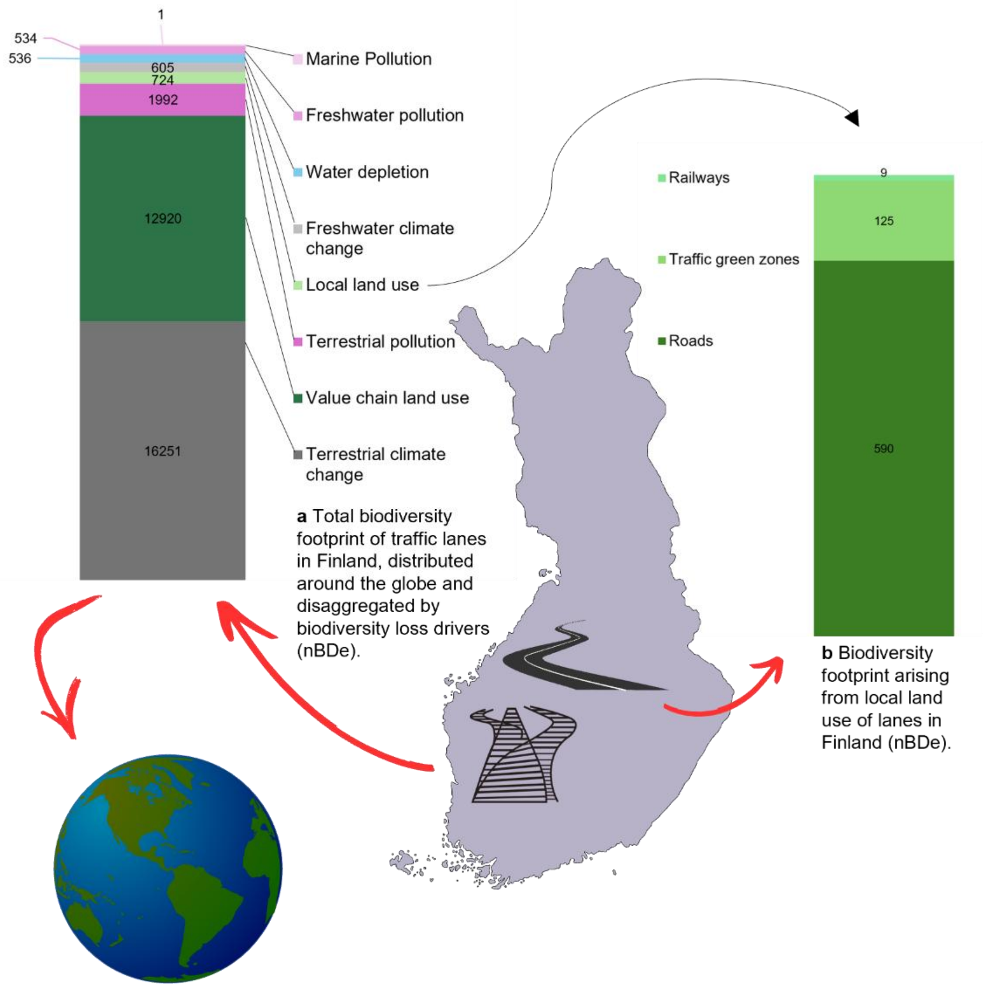

Fig. 5: Life cycle and local land use biodiversity footprints of traffic lanes in Finland. a, Life cycle biodiversity footprint of traffic lanes, disaggregated by the driver of biodiversity loss. **b,** Biodiversity footprint arising from local land use by traffic lanes in Finland. Footprints are expressed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

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[37]. 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[21] and increase climate-mediated extinction risk[13,14].

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[43]. 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 accounting is therefore essential for evaluating the full consequences of national transportation systems.

Biofuels have been promoted in Europe and globally as a means to reduce greenhouse gas emissions from transport[38,39]. 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[40], and that land-use changes associated with biofuel production have affected local species richness across the globe[41]. 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[38,42,43]. The biodiversity and climate impacts of biofuels therefore depend strongly on feedstock type, feedstock production location and fuel-conversion pathway[38,41,43]. 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[38,41], their impacts can also be significant, particularly if lower energy density of feedstock requirements increase land demand[41].

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[22,44,45], while also offering potential synergies between biodiversity, climate and health[46,47].

Traffic lanes were the other major contributor to the biodiversity and carbon footprints of the Finnish transportation system. While 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[3,8,48,49], 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[50,51], and that upstream material production contributes to energy use, pollution and greenhouse gas emissions[25,50,51]. Finland's approximately 454,000 km road network[52], therefore represents both a direct land use pressure and a substantial value chain burden. Globally, with more than 21 million km of roads[53], such displaced impacts may be an important but under-recognized component of transport-related biodiversity loss.

Several limitations should be considered. We could not include road-use-phase effects such as leachate production and rolling resistance[54,55], nor habitat fragmentation, although fragmentation and disturbances caused by road network contribute substantially to global terrestrial biodiversity loss[9]. 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[32] (Extended Data Fig. 4). Biofuel impacts were particularly uncertain because Finnish fuel consumption statistics do not distinguish pure from blended biofuels or specify feedstock composition[56]. Greater transparency from biofuel producers and retailers is needed to assess whether biofuels deliver genuine climate and biodiversity benefits or shift impacts elsewhere.

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[9,57,58]. 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[18,59], even though electric vehicle production requires more materials and energy than conventional vehicles[60,61]. These upstream impacts can be reduced through efficient battery recycling[62–64], moderate vehicle size[63–65], and environmentally sustainable electricity production[59,60,62–64]. Also, biogas may provide benefits in some contexts, but its biodiversity and climate outcome depend strongly on feedstocks used[66,67]. Climate-oriented transport policy can therefore create biodiversity trade-offs if value-chain impacts are ignored[68–70].

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[10,54,55,55]. However, technological substitution alone is unlikely to be sufficient. Because consumption is a major driver of biodiversity loss[12,57], 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[45,50,71]. Such shifts can reduce carbon emissions, biodiversity pressures and infrastructure land requirements, while also supporting health benefits[47].

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.

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[36,72,73]. By applying the Biodiversity Equivalent Impact Assessment method, BIOVALENT[32], 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[32].

Life cycle assessment typically follows four steps defined in the ISO 14044 standard: 1) defining goal and scope, including system boundaries and functional units 2) compiling the life cycle inventory in which the inputs and outputs are allocated across the life cycle 3) assessing the environmental impacts (called life cycle impact assessment, LCIA) and 4) interpreting the LCIA results[74,75].

Finnish transportation system and system boundaries

Finland is a country located in Northern Europe. Its total area is 338 491 km^2, of which 304 000 km^2 is land area[76]. In 2025, Finland had 5.6 million inhabitants[77].

Transportation systems consist of traffic lanes, all modes of transport, transport services, telecommunications networks, vehicles and the systems controlling the traffic[21]. Based on this definition, we outlined the system boundaries of the research. The sub-systems considered were 1) vehicles, 2) traffic (passenger and freight) 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 Extended Data Fig. 1.

Traffic control systems and management and telecommunication systems were scoped out of this study. We also outlined foreigners' travel to Finland, Finnish residents' travel abroad, and trips and freight abroad by vehicles registered in Finland out of this study. National transportation statistics do not allow distinguishing whether a vehicle is registered in Finland or abroad[78] nor whether a traveller is Finnish or foreign. Conversely, trips abroad by vehicles registered in Finland should be included in Finnish traffic statistics. Because these distinctions cannot be made, it has been stated that these inaccuracies partly compensate for each other[78]. Thus, it can be assumed that the travel of Finnish residents cannot be distinguished from foreign transport statistics either, in which case the travelling of Finnish people abroad is included in the biodiversity and carbon footprint of the country of destination. Furthermore, international air transport and shipping is not included in the Finnish emission calculations[79] and they are subject to separate international climate goals[80,81].

Transportation activities of defensive forces and border guard detachment were also scoped out of this study, although including them in the future assessments would be important for facilitating sustainable transportation in these sectors as well.

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[82] and the Transport and Communications Agency, Traficom[83]. In addition, reports published by transportation sector organisations were used and information requests were submitted when more specific data were needed. Some 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.

Because the consumption data of the Finnish transportation system appeared to be fragmented (Extended Fig. 4), we had to use input data from different years. For example, most of the data on number of vehicles were from 2023 or 2024, whereas data on transport infrastructure, such as ports and railway stations, had to be taken 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.

The consumption data and functional units used in the assessment are described in the sections of each sub-system below. 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.

Modelling biodiversity impacts

We combined ecoinvent 3.10.1 Cutoff and APOS version[84–86] and the ReCiPe2016 v.1.03 Midpoint (H) method[87] 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[32,87]. Ecoinvent is a global life cycle inventory database providing supply chain data of different sectors' material and energy flows[84]. 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[87]. 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.

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[32,35]. 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[35]. 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[32].

We used Rstudio version 4.4.1. to create the impact factors. We used R-script generated by ref[88]. 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[32,89], see equation (1) below. This indicator of biodiversity footprint combining biodiversity impacts across all ecosystem types is called the biodiversity equivalent, BDe[32].

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

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[32]. 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 ref[32].

For terrestrial ecosystems, the environmental pressures included in the biodiversity footprint assessment were climate change (kg CO_2 e), land occupation (m^2 of annual and permanent crops, pasture, urban land use, extensive and intensive forestry), and pollution caused by photochemical oxidant formation (kg NO_x e) and terrestrial acidification (kg SO_2 e). Because the land use in ReCiPe 2016 is expressed in annual crop equivalents[87], we modified the method in openLCA by adding an impact category that measures land occupation in square meters and used this impact category instead. The details of the modification are provided in Supplementary Methods.

For freshwater ecosystems, the environmental pressures considered were water depletion (m^3), phosphorus pollution (kg P e) and climate change (kg CO_2 e). For marine ecosystems, the environmental pressures considered were nitrogen pollution (kg N e)[32]. The GHGs included in climate change impacts were carbon dioxide, nitrogen dioxide, and methane.

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

Electricity consumption

We created an ecoinvent process for electricity production in Finnish electricity grid in 2023. This process was used for electricity consumption input flows for processes such as transport station operations and electric vehicle traffic. Creating the ecoinvent process is described in detail in Supplementary Methods and Supplementary Table 1.

Production and maintenance vehicles

The assessment of the biodiversity and carbon footprint of vehicle production was 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.

Traffic

For traffic, we used data on vehicle kilometres travelled (VKT), passenger kilometres travelled (PKT) or ton kilometres travelled (TKT). Thus, the functional unit of traffic was either kilometres, passenger-kilometres, or ton-kilometres. The impact assessment of biogas consumption in passenger car traffic was based on the amount of produced biogas (kg), while for leisure boating the assessment was based on consumed fuels (litres).

To avoid double counting, footprints of traffic were assessed using a well-to-wheel (WTW) analysis, in which the impacts of fuel production, transport and consumption are included[90]. This approach was used, because the life cycle impacts of vehicles and traffic lanes were assessed separately. To implement this, we modified the relevant ecoinvent processes in openCLA by removing the input and output flows related to the vehicle and transport infrastructure. The detailed process modifications are provided in Supplementary Table 2.

For the time series assessment, we multiplied the annual traffic volumes in 2016 – 2023 by the corresponding impact factors to derive the annual biodiversity and carbon footprint of traffic. To assess the impacts of traffic over the entire life cycle of vehicles, we estimated the average annual traffic volume of each transport mode using on transport statistics from 2016 – 2023. These average annual traffic volumes were then multiplied by the estimated life span of corresponding vehicle type to determine how much these vehicles are driven during their operating life. The used life spans are provided in Supplementary Table 3. These values were then multiplied by the corresponding impact factors for pollution and climate change in each ecosystem type.

The impacts of land use and water depletion caused by traffic were calculated once, by multiplying the average annual traffic volume of each transport mode with the respective impact factors. These drivers are not necessarily be cumulative similarly in the same way as pollution or GHG emissions. Thus, multiplying them by the full life cycle traffic volume would likely overestimate the amount of land use and water depletion and thus, their impacts. The land use impacts of biofuels were estimated differently (see Estimating the land use caused by biofuels).

Because ecoinvent version 3.10.1 does not include a process for flex-fuel passenger car transport, we used midpoint characterization factors from ref[91] to assess the biodiversity and carbon footprint of driving flex-fuel passenger cars, i.e. cars using E85 fuel, a blend of 85 % bioethanol and 15 % fossil petrol. For the land use impacts of E85 consumption, we used the midpoint characterization factor from the ecoinvent process for E85 production (See Supplementary Methods and Supplementary Table 2 for details), as ref[91] did not provide characterization factors for land use.

For biodiesel, we created an ecoinvent process. Based on the ecoinvent process "transport, freight, lorry 28 metric ton, fatty acid methyl ester 100% | Cutoff, U – CH", we assumed, that half of the consumed biodiesel is produced from palm oil, and the other half from a mix of animal fats and vegetable oils.

For biogas, we assessed the footprints using the ecoinvent process for biomethane production in kilograms due to the lack of suitable WTW characterization factors for biogas use in midsized passenger cars that could be applied within the BIOVALENT method (Extended Data Fig. 4). A more detailed description of impact assessment of biofuels is provided in Supplementary Methods.

Ecoinvent version 3.10.1 does not include a process for leisure boating. However, leisure boating is a popular activity in Finland, and fuel combustion during the boating season has been estimated to generate around 155,800 tonnes of carbon dioxide emissions annually[92]. Therefore, we created ecoinvent processes in openLCA for petrol and diesel consumption in leisure boating. The detailed methods used to construct the processes are provided in Supplementary Methods.

Estimating the land use caused by biofuels

The land use impacts of biofuels arising from traffic over the life cycle of vehicles were assessed differently from those of passenger car traffic using fossil fuels. This was done because assuming that land use from biofuel consumption is non-cumulative would likely underestimate the impacts, as biofuel consumption is known to drive land use change[41,93]. No data were available on how much biofuels contribute to cumulative global land use change per unit of consumption, in this case, per kilometre driven. Therefore, we used the national land occupation and land transformation flow inventory compiled by ref[94], which provides data on land transformation in 17 land use classes and of land occupation in 21 land use classes across 225 countries.

To estimate the land use impacts of biofuel consumption, we calculated from the country level inventory data[94] the average land occupation of the relevant land use class (ha*year) and the average land transformation of that land use class (ha). We then calculated how much annual transformation accounts from the annual occupation, T_O, as follows:

$$T_O = \frac{\bar{x}_{LT}}{\bar{x}_{LO}} \qquad (2)$$

Where $\bar{x}_{LT}$ is the average land transformation and $\bar{x}_{LO}$ is the average land occupation for the land use class.

For bioethanol, we used the land use class “permanent pastures and meadows” based on the ecoinvent process for E85 production. The transformation accounted for - 3 % of occupation. Thus, on average, the area of permanent pastures and meadows decreases by 3 % every year in each country included in the inventory[94] due to increases in other land use classes.

To estimate the land use change associated with E85 consumption during the operating life of passenger cars in Finland, we multiplied -0.03 by the life span of passenger car (22.5 years) (Supplementary Table 3), yielding a value of -0.63. The resulting change factor for the new land use value is therefore 0.37. This value was then multiplied by the midpoint characterization factor for land use in E85 production to estimate the land use change due to E85 consumption.

The calculation procedure for land use change and its incorporation into midpoint characterization factor was the same for biodiesel and biogas, with different land use classes. For biodiesel we used the land use class “permanent crops” and for biogas “planted forest, extensive forest” based on ecoinvent data.

In the case of biodiesel, land use in permanent crops increases by 1 % annually and for biogas the land use in planted forest increases by 0.02 % annually.

The adjusted midpoint characterization factors were then multiplied by the PDF values for land use from LC-IMPACT to derive the damage level impact factors. These impact factors were subsequently multiplied by the corresponding traffic volume over the life span of the vehicles to assess the biodiversity loss caused by biofuel consumption.

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[38,95].

Transport infrastructure

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^2). For multi-storey car parks, the impact assessment of was based on their total capacity (m^3).

To better represent the impacts of Finnish transport stations, the ecoinvent process data for ports were refined using average consumption data of Finnish ports. For airports, we scaled the endpoint impact factors of each Finnish airport according to the average number of landings relative to those of the ecoinvent process model airport, Zurich. Detailed modifications to ecoinvent data are provided in Supplementary Methods.

Because ecoinvent version 3.10.1 does not include processes for construction of bus depots, railway and metro stations (Extended Fig. 4), we used ecoinvent process for hall construction to approximate these impacts. As this process does not include heat, we collected heat consumption data (MWh) for metro and railway stations and assessed the biodiversity and carbon footprint of due to this heat consumption.

Since data of the area of railway stations and bus depots were available, the biodiversity footprint of local land use was calculated by multiplying the occupied area (m^2) by the characterization factor for urban land occupation, using the median value for Finland expressed in PDF/m^2 from LC-IMPACT. The 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[96], in this case, urban land use. The PDF values of land use were then converted to biodiversity equivalents by weighing them with the share of all plant and animal species that exist in terrestrial ecosystems[32,89].

Traffic lanes, lay-bys, and parking lots

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

The biodiversity footprint of local land use of traffic lanes, lay-bys and parking lots was assessed separately from their life cycle impacts to obtain a more precise estimate of land use related biodiversity footprint, rather than relying solely on modelling. Accordingly, when assessing the life cycle impacts, we removed land occupation flow from the ecoinvent process inputs in openLCA to avoid double counting (see Supplementary Table 2).

The biodiversity footprint of local land use was calculated by multiplying the occupied area (m^2) of lanes, lay-bys, and parking lots by the characterization factor for urban land occupation, using the median value of Finland expressed in global PDF/m^2 from LC-IMPACT.

We also accounted for land use impacts from traffic green zones by multiplying their total occupied area by the average of the characterization factors for pasture and urban land occupation (global PDF/m^2, median value for Finland). Using global PDF to estimate the biodiversity footprint of local land use of traffic lanes in Finland allows comparing the results with impacts arising from the value chains of traffic lanes. Lastly, the PDF values of land use were converted to BDe values as described in the paragraph "Transport infrastructure".

Comparing the biodiversity and climate footprint of different transport modes in relation to average passenger number

To estimate the biodiversity and climate impacts per passenger kilometre, the biodiversity and carbon footprint 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:

$$N_{\frac{pass.}{VKT}} = \frac{\text{Total number of passengers per vehicle type in 2023}}{\text{Total VKT of vehicle type in 2023}} \quad (3)$$

The data were obtained from the national Public Transport Performance Statistics[97]. For trams we took an average of the passenger numbers in trams (streetcars) and light rail. Because no equivalent data were available for passenger cars for 2023, we used average passenger number for passenger cars in Finland from 2016[98].

Transport scenarios

We created four scenarios for the biodiversity and carbon footprint 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 passenger cars in transport ranged from 71-73 % for petrol and 27-29 % for diesel passenger cars. The detailed methods used to derive the shares are provided in Supplementary Methods.

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 %.

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 passenger cars.

To estimate the VKT by motive power in each scenario, we multiplied the annual VKT of all passenger cars in 2016 – 2023 by the scenario specific shares of passenger cars in transport. These VKTs were then multiplied by the corresponding impact factors to derive the biodiversity and carbon footprint for each scenario.

Data availability

The datasets used and created in this paper are available at Zenodo: https://doi.org/10.5281/zenodo.21310649

Code availability

The code used in this paper is available in Zenodo: https://doi.org/10.5281/zenodo.21035721

Supplementary Information

Supplementary Information is available at Zenodo: https://doi.org/10.5281/zenodo.21310649 (Supplementary Methods, Supplementary Tables 1-3 and Supplementary References)

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Contributions

JSK, SB and SEG conceptualized the study. VL, JSK, SB and SEG, designed the study and VL performed the analyses with support from JSK, SB and SEG. VL collected the data with help of EJ and processed the data. VL produced the figures and wrote the original draft of the paper. VL, JSK, SB and EG contributed to the editing and reviewing of the manuscript.

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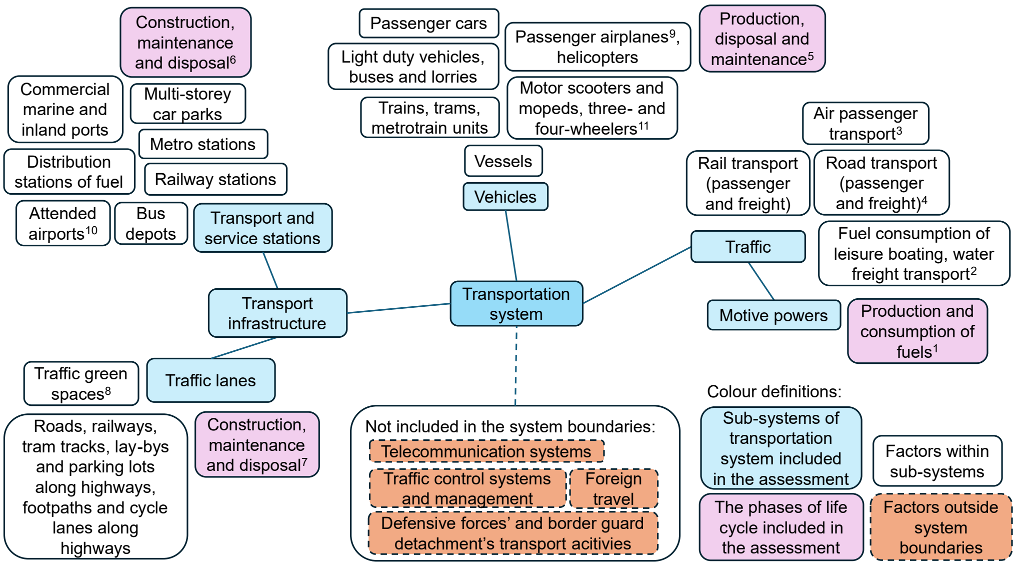
Ethics declarations

Competing interests

The authors declare no competing interests.

Extended data figures



Extended Data Fig. 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 traffic volume 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.

Extended Data Table 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 transportation system	Share of sub-system's biodiversity footprint (%)	Share of sub-system's carbon footprint (%)	Share of total biodiversity footprint (%)	Share of total carbon footprint (%)
Production of vehicles				
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 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-wheelers	0.0	0.0	0.0	0.0
Trams	0.0	0.0	0.0	0.0
Locomotives and steam locomotives	0.5	0.4	0.1	0.0
Wagons (freight)	0.9	0.9	0.1	0.1
Wagons (passenger)	0.1	0.1	0.0	0.0
Motor train unit (long distance)	0.3	0.3	0.0	0.0
Motor train unit (regional)	0.1	0.1	0.0	0.0
Metrotrain units	0.0	0.0	0.0	0.0
Barges and other engineless ships	0.4	0.4	0.0	0.0
Bulk carriers for 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 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 long-haul belly-freight aircrafts	0.6	0.6	0.1	0.1
Maintenance of vehicles				
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 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-wheelers	0.1	0.1	0.0	0.0
Trams	0.0	0.0	0.0	0.0
Locomotives and steam locomotives	0.8	0.8	0.0	0.0
Wagons (freight)	4.0	4.1	0.1	0.1
Wagons (passenger)	0.3	4.1	0.0	0.1
Motor train unit (long-distance)	0.1	0.1	0.0	0.0
Motor train unit (regional)	0.8	0.8	0.0	0.0
Metro train units	0.0	0.0	0.0	0.0
Barges and other engineless ships	0.8	0.7	0.0	0.0
Bulk carriers for 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 vessels	7.5	6.7	0.1	0.1
Other vessels	4.3	3.9	0.1	0.1
Traffic				
Electric p. cars	0.0	0.0	0.0	0.0
Diesel p. cars, fossil diesel	11.8	11.9	5.5	6.2
Diesel p. cars, biodiesel	1.2	1.1	0.6	0.6
Petrol p. cars	47.4	48.4	22.2	25.4

Flexfuel (E85) p. cars	0.0	0.0	0.0	0.0
Gas p. cars, natural 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 motive power	0.0	0.0	0.0	0.0
Petrol/gas (biogas) p. cars	0.1	0.1	0.0	0.0
Buses	5.1	4.8	2.4	2.5
Motor scooters, mopeds, three- and four-wheelers	0.8	0.8	0.4	0.4
Haulage driven by vans	12.2	12.2	5.7	6.4
Lorries (weight 3500 - 7500 tonnes)	0.2	0.2	0.1	0.1
Lorries (weight 7500 - 16 000 tonnes)	0.5	0.5	0.2	0.3
Lorries (weight 16 000 - 32 000 tonnes)	2.0	2.0	1.0	1.1
Lorries (weight 16 000 - 32 000 tonnes), biodiesel	0.3	0.2	0.1	0.1
Lorries (weight more than 32 000 tonnes)	12.0	12.0	5.6	6.3
Train passenger transport (long-distance and regional)	0.1	0.1	0.1	0.1
Metro passenger transport	0.1	0.1	0.0	0.0
Tramway passenger transport	0.0	0.0	0.0	0.0
Freight transport, electric train	0.5	0.5	0.2	0.2
Freight transport, diesel train	0.9	0.8	0.4	0.4
Air passenger transport	1.3	1.2	0.6	0.6
Vessel freight transport, inland waterways	0.0	0.1	0.0	0.0

Vessel freight transport on coastal waterways, bulk carriers	0.4	0.2	0.2	0.1
Vessel freight transport on coastal waterways, tankers	0.1	0.0	0.0	0.0
Log floating	0.1	0.1	0.0	0.1
Dredging masses 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	0.31	0.0	0.1	0.0

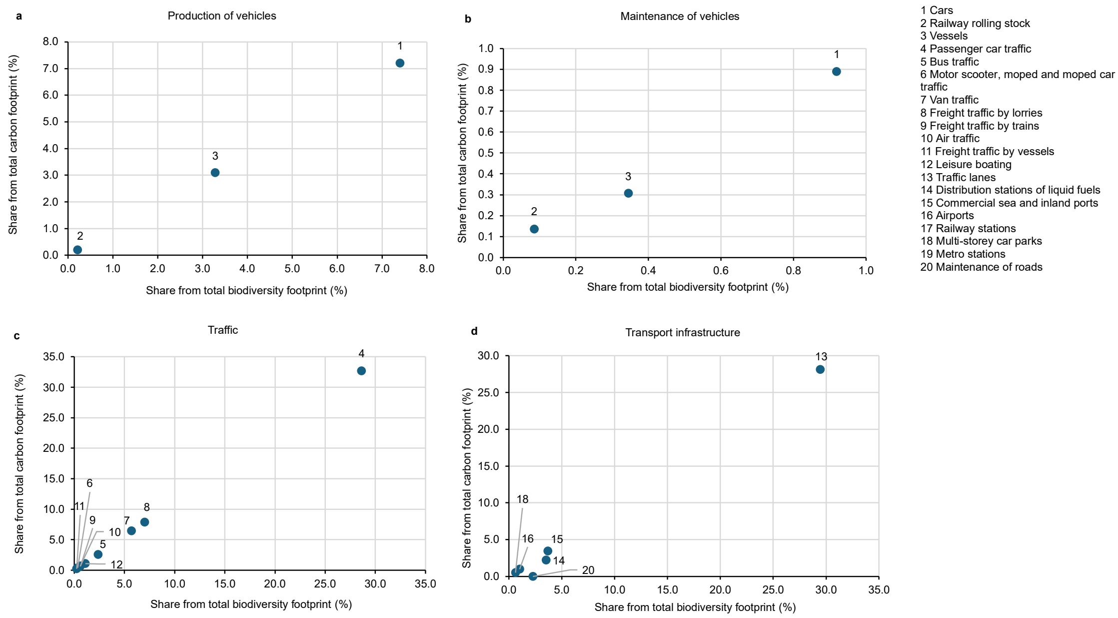
lanes along highways				
Maintenance of street network of municipalities	1.31	0.0	0.5	0.0

Extended Data Table 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.

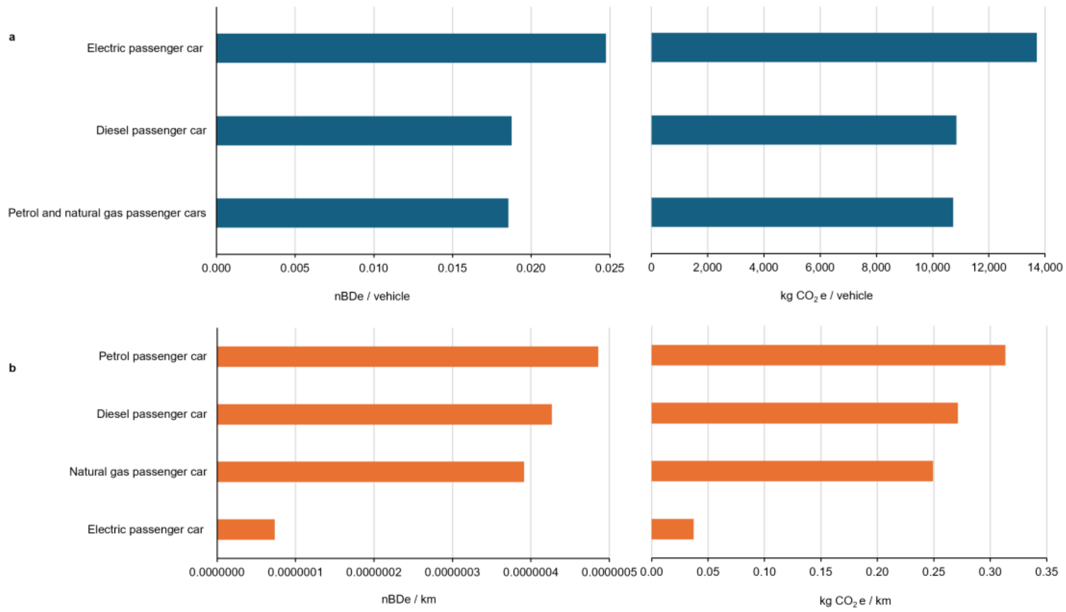
	Terrestrial ecosystems			Freshwater ecosystems		
Factors within sub-system	Land use	Pollution	Climate change	Pollution	Climate change	Water depletion
Production, vehicles						
Passenger cars	2 %	7 %	91 %	19 %	29 %	52 %
Vans	4 %	14 %	82 %	33 %	22 %	45 %
Buses	3 %	9 %	88 %	23 %	31 %	46 %
Lorries	2 %	8 %	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 %
Maintenance, vehicles						
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 %
Traffic						
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 %
Transport infrastructure						

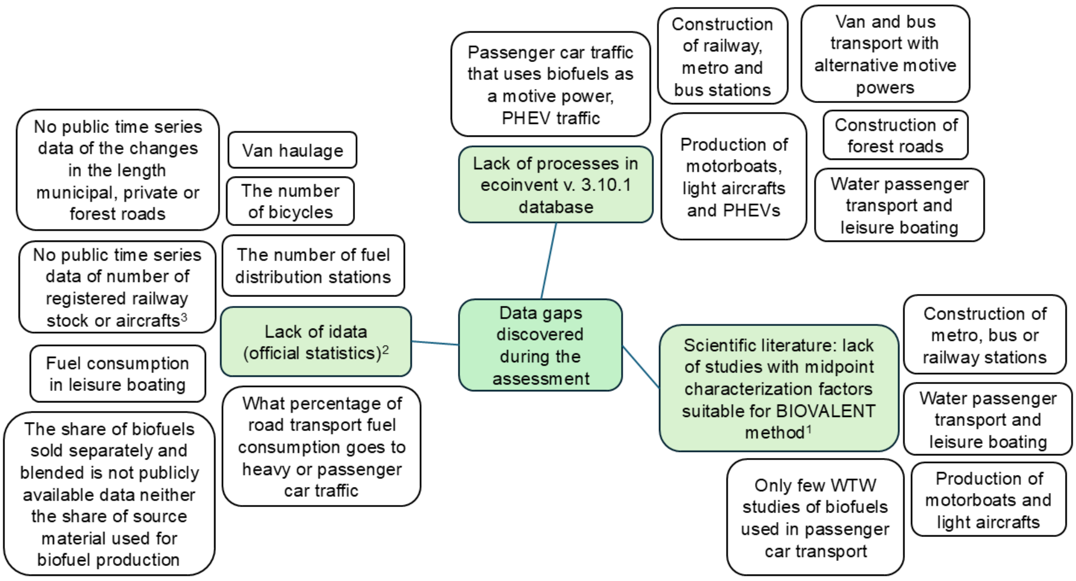
Roads	4 %	14 %	82 %	5 %	75 %	20 %
Train, tram and metro tracks	4 %	8 %	88 %	16 %	43 %	41 %
Lay-bys and parking lots along highways	1 %	10 %	89 %	8 %	58 %	34 %
Distribution stations of fuels (liquid and gas)	36 %	10 %	54 %	22 %	22 %	57 %
Commercial sea and inland ports	5 %	14 %	81 %	8 %	74 %	18 %
Airports	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 %



Extended Data Fig. 2: 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.



Extended Data Fig. 3: 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.



Extended Data Fig. 4: Mind map of the data gaps identified during the assessment, categorized into data gaps in databases, scientific literature and data. 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 suitable for 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) In these cases, only the most recent updated data are available in public registers, rather than full time-series data.