Journal of Environmental Management 385 (2025) 125475

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Pixels, chisels and contours - technical variations in European road traffic noise exposure maps

Jeroen Staab [a,b,*], Ariane Droin [a,c], Matthias Weigand [a], Marco Dallavalle [d], Kathrin Wolf [d], Arthur Schady [e], Tobia Lakes [b], Michael Wurm [a], Hannes Taubenböck [a,c]

[a] German Remote Sensing Data Center, German Aerospace Center (DLR), Oberpfaffenhofen, Germany
[b] Geography Department, Humboldt-University Berlin, Berlin, Germany
[c] Institute for Geography and Geology, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
[d] Institute of Epidemiology, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, Germany
[e] Institute of Atmospheric Physics, German Aerospace Center (DLR), Oberpfaffenhofen, Germany

ARTICLE INFO

Keywords:
European noise directive (END)
Topological errors
Open data publication
Transport emissions
Road traffic noise
Environmental noise exposure

ABSTRACT

Motorized traffic often causes road noise directly in front of our homes and windows. Yet long-term exposure to noise impact life's quality and can potentially cause negative effects on human health. Furthermore, social and behavioral effects have been measured. To protect people's health and well-being from such noise, the European Noise Directive (END, 2002/49/EC) obliges countries to produce strategic noise maps every five years for large agglomerations and along major roads, which are then used for noise action planning. Besides that, the official noise maps are a valuable data source for environmental exposure analyses. However, the END has some limitations. The definition of urban agglomerations is vague, different input parameterizations lead to data inconsistencies across administrative units, undefined post processing methods introduce geometric artifacts, and topological errors incompliant to the common Simple Features Implementation Specification hinder working with the published geodata. The aim of this article is to provide practical insights for end-users and stipulate for concise regulations. Moreover, we highlight that these variations limit the comparability of maps in environmental impact assessments. We compile 84 separate noise assessments in Germany reported according to the END to review shape and structure of the geographic data. Graphical representations are used to show in particular how vertices are connected to polygons in noise contour maps and that these geometric alterations effect the eventual statistics on exposed population shares. We aggregate spatial metrics to assess the reported data's spatial properties in an automatic manner, e.g. when receiving data in future mapping rounds. Along with our quality assessment, a nation-wide dataset on road traffic noise was produced. Depicting the yearly averaged noise level indicator L_{den}, which integrates exposure at day, evening and night, for 2017, it serves as common ground for environmental health analyses. The examination of different raster to polygon conversion implementations is fundamental to other geodata managers outside the domain of noise mapping, as well.

1. Introduction

Increased land use, population, industry, and traffic impact ecosystems, lead to poor air quality, reduced green spaces, and more noise (Han et al., 2018; McMichael, 2000; Kalisa et al., 2022). Referring to such toxic loud and unpleasant sound, a plethora of studies have shown that, noise pollution is a major concern for many communities as it can lead to a range of adverse health effects including annoyance, sleep disturbance, cardiovascular problems and even cognitive impairment in children (Stansfeld, 2003; van Kempen and Babisch, 2012; Gidlöf-Gunnarsson and Öhrström, 2007; Michaud et al., 2023; Guski et al., 2017; Basner and McGuire, 2018; Van Kempen et al., 2018; Clark and Paunovic, 2018; Schubert et al., 2023; Rompel et al., 2021; The Lancet Regional Health – Europe, 2023; Gu et al., 2023). In Europe alone, the European Environmental Agency (EEA) attributes 12,000 premature deaths every year to noise exposure (European Environment Agency, 2020). In addition to the absence of green spaces, urban heat, and air pollution, the acoustic environment - and road traffic noise as a

This article is part of a special issue entitled: urban sound environment published in Journal of Environmental Management.

* Corresponding author. German Aerospace Center (DLR), Münchener Straße 20, 82234, Weßling, Germany.
E-mail address: Jeroen.staab@dlr.de (J. Staab).

https://doi.org/10.1016/j.jenvman.2025.125475
Received 13 August 2024; Received in revised form 4 April 2025; Accepted 19 April 2025
Available online 5 May 2025

particular component of the latter - can have a significant impact on the overall quality-of-life of people living in affected areas (Jones et al., 1981; Passchier-Vermeer and Passchier, 2000; Huang and Seto, 2024; Camerin and Longato, 2024; Hernández and Camerin, 2024; Ivanović et al., 2014; Zapata and Honey-Rosés, 2022) as well as on wildlife and its habitat (Brumm, 2013; Buxton et al., 2017; Francis et al., 2012, 2017).

Mapping noise is crucial in order to identify areas where noise levels are harmful to human health and the environment. Therefore, noise maps are vital tools for assessing and implementing effective noise mitigation strategies and protecting human health as well as the environment. Among all other noise emitting sources considered, road traffic noise is almost ubiquitous present (European Environment Agency, 2020) and therefore of particular interest in the following study perused from a geographical perspective. Producing a spatial representation of noise exposure, however, is challenging. This is because in-situ measurements using microphones does retrieve accurate data on the present sound pressure levels, but does not scale economically across large areas and over long time-spans due to high spatio-temporal variability (Quintero et al., 2018). Instead, to map environmental noise across cities and countries, noise prediction models are commonly used (Meller et al., 2023; Steele, 2001; Garg and Maji, 2014; Tiwari et al., 2023; D. Khan and Burdzik, 2023; J. Khan et al., 2018; Meller et al., 2023; Qin et al., 2024; Fiedler and Zannin, 2015). The European Noise Directive (END) (2002/49 /EC, 2002) aims at reducing the harmful effects of exposure to environmental noise by obliging member states to produce noise maps and develop subsequent action plans every five years.

Comparing European noise maps between cities or even countries, however, remains difficult for both legal and technical reasons. The END obligation is vague in Article 3, when defining the spatial entities. Specifically, section *k* refers to urban agglomerations as a delimited territory "*having a population in excess of 100,000 persons and a population density such that the Member State considers it to be an urbanized area*". This allowance for consideration results in variability in how urban areas are delimited. In Germany for example, the Federal Immission Control Act (Federal Immission Control Act - BImSchG, 1974) §47b.3 sets a population density threshold of above 1,000 inhabitants per square kilometer. But also, areas affected by major roads with more than 3 million vehicles passing per year need to be mapped (END Article 3 section *n*), independent of their association to urban agglomerations. That said, this completely omits critical noise levels emitted from less frequented roads. And comparing the sections *k* and *n* of Article 3, different minimal mapping units are applied for between urban agglomerations and peripheral areas. Consequently Riedel et al. (2014) concluded, that noise effects on health might be underestimated. Beyond these two different mapping obligations, detailed abstractions, of how many vehicles, of which kind, at which driving speed, on what surface and under which environmental conditions need to be condensed into a noise mapping method. Before a pan-European harmonization was developed (Kephalopoulos et al., 2014), these were for example NORD2000 used in Nordic countries (J. Khan et al., 2021), CoRTN and its free implementation TRANEX common in the Anglo-Saxon countries (J. Khan et al., 2021; Faulkner and Murphy, 2022), NMBP in France (Murphy and Douglas, 2018; Meller et al., 2023), or, amongst others, RLS-19 and its precursor RLS-90 in Germany (Meller et al., 2023). Moreover, just collecting the input data for these methods is actually a further subject to the respective region – e.g. German recommendations for traffic surveys (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012). It is thus not surprising, that in a recent review of 749 strategic road traffic noise maps gathered from the END reporting and other sources, Khomenko et al. (2022) found variability in the available data caused by different noise mapping methods and noise exposure assessment. However, the study also stressed the different data formats and concluded that further efforts to standardize the noise data are needed as well as to increase data availability and quality.

With respect to national assessments using publicly available noise data, this study aims to technically review the German L_{den} strategic noise maps for road traffic from the 2017 reporting round. To that end, END-compliant noise maps are assessed with the goal of providing an analysis-ready and thoroughly documented dataset. Currently, most European noise maps do so using polygons (Khomenko et al., 2022). In the present study, we focus our investigations into this geodata format specifically, as formal inconsistencies can break geoanalytical pipelines. We build upon the guidelines established by the Open Geospatial Consortium (OGC) including a set of definitions for encoding spatial data, in particular, vectorized polygons (Herring, 2011). Against this backdrop, we technically review European noise maps in two fashions, in order to discuss implications for environmental exposure assessment and health analyses. (A), we scrutinize the vectorized geodata at the vertex level. Thereby, semantic and technical differences between independently reported END road traffic noise datasets are identified. Users of the data are so informed about regional variations biasing the certainty in national comparisons. Germany was chosen as a study region as it represents a European country organizing its noise reporting locally and on a federal basis. (B), we reproduce a common processing steps conducted during the reporting in a detailed case study, converting the original raster outputs from the engineers contracted by one urban agglomeration, the city of Koblenz, to polygons. Therewith, we help to better understand how the legally required contour maps are structured and represented in geographic datasets. Using the acoustical engineer's original raster output, we exemplify geometric artifacts produced during the conversion step that result from different GIS software suites (with different conversion algorithms respectively). We verify the hypothesizes, that these geometric alterations of contour shape and covered areas potentially affect the respective population counts exposed to critical noise levels using population data. Together, both methodical strings are a diligent documentation of the reported strategic noise maps provides insights to the data's genesis. It does however also raise the question, to which extent the federated reporting system introduce variance beyond the else strictly regulated framework of the END? Addressing policy makers, we propose spatial metrics for automatic data quality checks for future noise reports. Along thereto, the supplementary output is a user-friendly dataset, now accessible as a cloud-optimized GeoTiff (Open Geospatial Consortium, 2019) and conform to Europe's Infrastructure for Spatial Information (INSPIRE, 2007). It allows answer the question, how comprehensively the publicly available noise maps cover the German territory. In pursuit of open and impactful research, the dataset has been linked to the national cohort (referred to as NAKO, Peters et al., 2022) and is now available for use in environmental health studies and beyond.

The remaining article is organized as follows: The Data and Methods section details data source, reviews the input and describes the steps needed to harmonize topology and unify *the data. A brief excursion into geospatial polygon production using various GIS algorithms aims to increase problem awareness for readers beyond the geoinformatics field. In the Results section we aggregate the documented challenges and present the final* unified *dataset along with zonal statistics on potentially exposed populations. In the Discussion, we analyze our findings in the context of existing literature, offer best practice suggestions for data management, and emphasize the implications of our work for environmental assessments. Lastly, we conclude by summarizing our contributions and providing directions for future research in the Conclusion section.*

2. Data & method

To address our aims, we structure our methodology in two workflows. Following the initial data retrieval, we exemplify the post-processing of European noise maps being most often reported as polygonal noise contours using an original raster map for the city of Koblenz (blue background in Fig. 1). This is used as a case study to assess the technical background of raster to polygon conversion. By combining the data with population data, geometric differences are set into the context of environmental impact assessments, i.e. to account for the

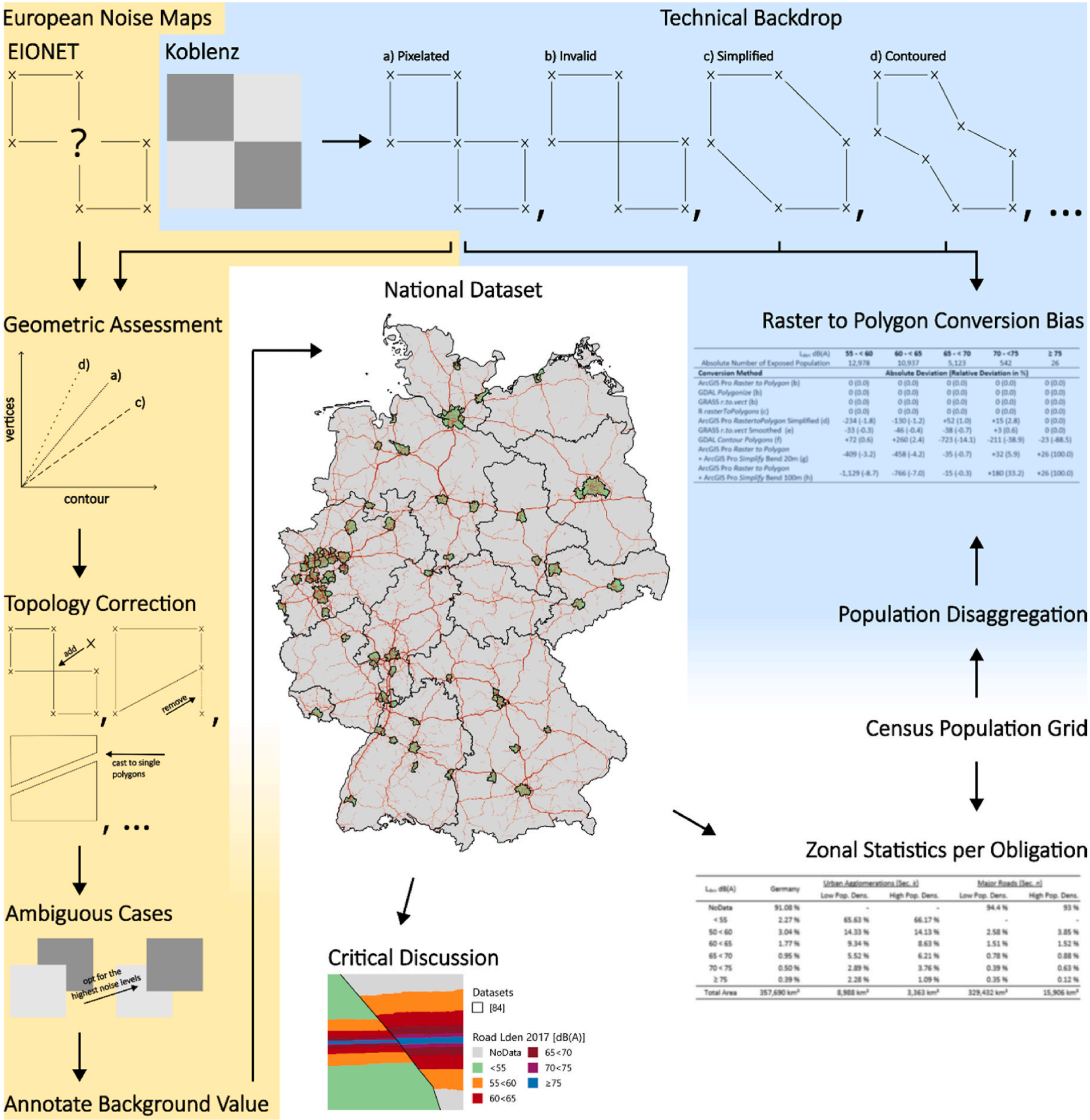

Fig. 1. Flowchart depicting the data review (blue) and the methodological process (yellow). Beginning with the data inputs on the top left, the figure can be read in two directions. Raster data from the city of Koblenz is used to review the technical backdrop of raster to polygon conversions using different conversion algorithms. Following the blue gradient, its different outputs are directly passed through to an assessment of the conversion bias, using auxiliary population data exemplary, while the pixelated output is also fed towards the unification workflow on the left. On this left side, reading vertically (yellow tone), the different methodical steps towards a well-documented, topologically corrected and unified national dataset are illustrated. The data (center) is then set into context. First, using population density and administrative data, and using detailed looks along the administrative responsibilities second.

differences in affected populations depending on the conversion technique. The most conservative geometry using pixelated polygons is then fed into the second methodical workflow (left vertical column with yellow background in Fig. 1). Together with the other strategic noise maps obtained from the EEA's environmental data repository EIONET, we pursue a comprehensive geometric assessment, followed by a topological correction and harmonization of ambiguous values. Eventually, the produced national dataset is further combined with population data from a census to affected populations on national scale.

2.1. European noise maps

The END states, that critical noise exposures beyond the threshold of 55 dB(A) L_{den} need to be delineated. Where the noise level indicator L_{den} integrates noise exposure during the day, evening, and night, with added penalties for the later hours to account for increased human sensitivity (Brink et al., 2018). The resulting strategic noise maps are a powerful resource for political decision-making, policy-making and planning (Murphy et al., 2020; Bhatia and Seto, 2011; Geraghty, 1996; King et al., 2011); and, as these political actions likely affect residents' reality, the data needs to be authentic to counter public skepticism (Marquet et al., 2024).

Beyond their utility within environmental policies, the publicly accessible datasets provide an important data source for different environmental health analyses, such as for measuring the correlation between noise levels and empirically collected health data (H. Xie et al., 2011; Zijlema et al., 2016; Wolf et al., 2023; Badpa et al., 2024; Faure et al., 2024; Eriksson et al., 2013; Zhuang et al., 2024; Herder et al., 2023; Voss et al., 2021). END noise data has, for example, also been used for uncovering relationships between noise levels and housing prices (Szczepańska et al., 2020; Morawetz et al., 2024) or for uncovering the spatial distribution of noise pollution in relation to socio-demographic groups from an environmental justice perspective (Shrestha et al., 2016; Lakes et al., 2013).

2.1.1. Data retrieval

Our data retrieval started at the EEA's central data repository EIONET, the environmental information and observation network. Sorted by the different legal obligations, EIONET held 249 gigabyte of data on ecosystems, climate change, human health and the environment, resource use and sustainability trends already in 2018 (European Environment Agency, 2021). With respect to road traffic noise in particular, three rounds of noise mapping have been published so far: 2007, 2012 and 2017. The results of the next mapping round, 2022, are still in preparation at the time of the submission of this article. Besides that, the reporting mechanism allows re-uploading revisions, such that the 2017 data retrieved in this study was the most recent, sixth, version from May 15th'2020.[1] The data is organized in a hierarchical file system. For each federal state, the data is gathered in an individual directory – so called envelopes with a respective unique identifier (referred to as *Envelope ID*).

Scoping German road L_{den} noise maps, all available Shapefiles were retrieved via the EEA'S reporting system. For future users it is important to note, that these strategic noise maps are source-specific. Whereas we focus on road traffic noise only - emitted by the vehicles' propulsion and tires interacting with the road surface, proportional to vehicle weight and driving speed (Federal Ministry of Transport and Digital Infrastructure, 1990) – also, separate data sets referring to rail and air traffic, as well as noise emitted by industrial sources is behold in the EEA's repository. Representative for whole Europe (Khomenko et al., 2022), most public authorities have delineated areas above the limit value of 55 dB(A) L_{den} at 5 dB(A) intervals using polygonal geodata formats. From the perspective of a geo-information-scientist, it is relevant to stress, that such a polygon needs at least four vertices. To denote a triangle, for example, one would draw four vertices, which are the points or corners connecting edges. These vertices are placed along the three corners, including a fourth vertex identical to the first to close the polygon. Otherwise, the triangular feature would be incomplete. All such incompliances to the OGC Simple Features Implementation Specification[2] encountered during our study, hereafter referred to as topological errors are illustrated in the supptementary Fig. S1. Most important though, along its geometrical information, a feature usually is annotated with values, e.g. noise levels in the present case. Single polygons behold information for one areal segment only. Respective data tables can become very long with repetitive annotations. Therefore, the standard optionally allows multiple geometries to be stored within one feature – e.g. one feature for each noise level class. These so-called *MultiPolygons*, having complex geometries, can increase computational costs but have better humanly-readable attribute tables.

Against this background, 51 of the obtained Shapefiles feature *MultiPolygon* geometries, 32 have *Polygon* geometries and 1 *MultiLineString* file, depicting noise level boundaries rather than areal polygons. Two polygon datasets included corrupt features *with an unparsable geometry* – polygons with non-matching first and last vertices or having two vertices only, and therefore rather looking like points or line features. These datasets could only be opened using the *Feature Manipulation Engine*[3] (FME), a commercial software suite specifically for handling spatial vector data. With it, the identified features were repaired manually before proceeding. With respect to the *MultiLineString* isolines reported for Koblenz, instead of interpolating them, we received the original, 10 x 10 Meter resolution engineers model output as an ASCII raster file upon request by the responsible administration, which – after assessing the raster to polygon conversions next – was converted to *MultiPolygon* and added to the data pool.

Closing the description of retrieved data, Table 1 provides an overview on the metadata for each federal state's envelope respectively. Referring to the German interpretation of urban agglomerations (BImSchG §47b.3), the envelope for Schleswig-Holstein was expected to contain only noise maps along major roads and both its major cities Kiel and Lübeck – but the total number of shapefiles within this envelope is in fact four (Table 1). It is therefore interesting to note, that several sub-urban communities north of the city state Hamburg were reported as additional shapefile in the neighboring federal state's envelope (see Fig. S3 for details). Additional columns provide detailed insights into the data's structure. Benchmarked against the OGC Simple Features Implementation Specification, we consider shapefiles not containing any invalid geometries as *OGC compliant*. We assessed the share of valid

Table 1
Overview of retrieved road traffic noise data. The column Envelope ID refers to EIONETs internal id used for bulk downloading the archives, while the Version specifies the date of the most recent revision. Three files, specified with + as prefix, had to be manually integrated into the workflow. The total number of files per federal state is delineated along the fractions of thereof files without invalid geometries according to the OGC Simple Features Implementation Specification and their geometries being organized as *MultiPolygon*.

Federal State	Envelope ID	Version	Number of Road L_{den} Files		
			Total	*Thereof*	
				OGC compliant	Multipolygon
Baden-Wuerttemberg	envxrliqg	2019-06-30	10	30 %	20 %
Bavaria	envxrliuw	2019-06-30	9	0 %	33 %
Berlin	envxrliyg	2018-08-30			
+ Aggroad ag1 (Berlin)	(Repaired w. FME)		1	0 %	100 %
Brandenburg	envxrlibg	2018-08-30	2	0 %	50 %
Bremen	envxrlifw	2019-12-30	2	0 %	0 %
Hamburg	envxrliiw	2018-08-30	1	0 %	100 %
Hesse	envxrlima	2019-06-30	6	0 %	100 %
Mecklenburg-Western Pomerania	envxrlipq	2018-08-30	2	0 %	100 %
Lower Saxony	envxrlita	2020-05-15	6	33 %	83 %
North Rhine-Westphalia	envxrliwq	2019-12-30	26	19 %	58 %
+ MRoad (Federal State)	(Repaired w. FME)		1	0 %	100 %
Rhineland-Palatinate	envxrlizg	2018-08-30	3	33 %	100 %
+ Aggroad ag3 (Koblenz)	(Rasterized via Email)		1	100 %	100 %
Saarland	envxrli3w	2018-08-30	2	50 %	100 %
Saxony	envxrli7q	2018-08-30	4	0 %	100 %
Saxony-Anhalt	envxrli_w	2019-06-30	3	0 %	100 %
Schleswig-Holstein	envxrljbw	2019-12-30	4	0 %	100 %
Thuringia	envxrljhg	2019-06-30	1	0 %	100 %

[1] https://cdr.eionet.europa.eu/de/eu/noise/df8/2017/colxrlfgg/.
[2] https://postgis.net/docs/ST_IsValid.html.
[3] https://fme.safe.com/solutions/data-types/gis-location-intelligence/.

files per envelope to increase the comparability. Similarly, the same ratio of files being organized as *MultiPolygon* was computed.

2.1.2. Raster to polygon conversion

Noise maps produced with engineering software such as CadnaA,[4] Soundplan[5] or IMMI.[6] These tools are validated through certification processes and the original outputs, often stored as raster files, are deemed appropriate for use in legal proceedings. It is, however, common for authorities to apply some kind of raster to polygon conversion. Actually, raster to polygon conversion (and vice versa) is a very common process in geoinformatics, and as such was already reviewed for example by Congalton (1997). Using ESRI's Arc/Info, he experimentally assessed its parameters and respective loss of details - particularly for smaller patches in relation to image resolution. Today, several algorithms exist to perform such conversions. But, to the best of our knowledge, there is no recent review of particular advantages and disadvantages between these tools. Also, the respective *Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure* (WG-AEN, 2007), does not include recommendations. Although, geometric alterations to the original engineer's output may potentially erode the trust put into the official data sets.

Comparing the different conversion methods with the 10 x 10 Meter resolution dataset for the city of Koblenz allowed for exemplifying different geometric artifacts produced during the raster to polygon conversion. We reviewed the most common GIS toolboxes and parameters (see supplementary S4). ArcGIS Pro, the two QGIS backends GDAL and GRASS, as well as the raster-package in R, convert raster inputs such that the edge of the output polygons is conform to the inputs raster's cell edges, hereafter referred to as pixelated output. However, there's also a plethora of options for geometries to be generalized, such that "*the polygons will be smoothed into simpler shapes […] in such a way that the polygons contain a minimum number of segments while remaining as close as possible to the original raster cell edges.*".[7] In order to regulate the complexity of the experimental set-up, the default parametrizations were preferred. Short explanations in S4 document the settings in further detail, laying out *at d*ifferent simplification tolerances using critical bends (Z. Wang and Müller, 1998) *using* ArcGIS Pro *Simplify Polygons* for example. The selected implementations were each applied to the engineered noise simulation raster output data received from the city of Koblenz. An exemplary map section showcasing the different representations is shown in Fig. 2.

Beyond a visual assessment, we conducted a quantitative assessment between the noise contour maps using objective and reproducible shape metrics (e.g. Angel et al., 2010). Therefore, the total number of vertices [N] and the contour length [m] were summed up. For reference, both values were put in relation to the area [N/m^2, m/m^2] and themselves [N/m]. This allowed for a quantitative assessment of the contours' density and smoothness, thus enabling an objective comparison of the input polygons. This descriptive analysis was conducted to identify potential trends, clusters, or anomalies within the data.

Population exposure assessment was conducted with the dataset received by the city of Koblenz. The goal of this step was to quantify the impact of different raster to polygon conversion algorithms on the estimations of population exposure. High resolution population data is rarely available, thus a variety of methodologies for disaggregating population on a finer scale are existing (e.g. Sapena et al., 2022). For locating the population at their home address, we disaggregated the most recent census data[8] available (100 x 100 Meter grids) onto the building level based on the floor area – the number of stories multiplied by the building's footprint (Barr and Cohen, 2014; Wurm et al., 2014) using a public LoD1 building model[9] - see S2 for reference. After applying all different raster to polygon conversion, we combined the contour maps with the disaggregated population data. All buildings are assigned to a specific census cell based on their centroid. The number of exposed persons per L_{den} noise contour interval was then compared to the original high-resolution 10 x 10 Meter raster map, allowing to quantify the impact of choosing raster to polygon conversion algorithms.

2.1.3. Geometric assessment

The quantitative shape metrics were computed for the 84 datasets as well. Complementary to the contour length per area [m/m^2], vertices density [N/m^2] and the respective ratio [N/m], the geometric appearance was screened manually. Qualitatively, we considered two aspects – shape (*pixelated*, *chiseled* or *contoured*) and resolution (~1 Meter, ~5 Meter, ~10 Meter, unknown). *Pixelated* vector data refers to raster to polygon conversion without generalizations or simplification and thus comprises polygons with rectangular shapes and consistent right-angled edges (c.f. Fig. 2b–c). For such polygonised datasets, the original raster resolution can easily be assumed. According to the END, noise maps need to be produced at least on a 10 x 10 Meter resolution. Guided by the experiences of comparing different conversion algorithms in Section 2.1.1, two distinct appearances of generalized geometries can be observed. Rough, triangular shapes with a persistence of rectangular structures (c.f. Fig. 2d–g–h) were encoded as *chiseled.* Conversely, we labeled round and organic-seeming shapes (c.f. Fig. 2e–f) as *contoured.* Obviously, the spatial resolution of generalized polygon data is rather difficult to measure, in particular, if no rectangular structures remain. Therefore, the third option - *unknown* - is used in ambiguous cases to denote uncertainty by the manual observer.

2.2. Topology correction

As noted in Table 1 above, the obtained strategic noise maps differed regarding their data structure and mode of formation. In addition to that, the GDAL driver detected several incompliances with the OGC standard. Frequent topological errors included self-intersecting polygons, characterized by the crossing of their outer borders. Imagining an exemplary square with four corners (five vertices respectively), the very same five vertices can be used to construct an hourglass (c.f. illustration in Table 3e). For geoinformation systems, this and other topological errors, obscure the areal delineations. The R-package "sf" (R Core Team, 2023; Pebesma and Bivand, 2023; Pebesma, 2018) includes tools to validate and repair spatial data. A minimal reproducible example, shown in S1, was used to develop our topology correction workflow. As topological errors may occur only locally, and with respect to the various *MultiPolygons* retrieved (c.f. Table 1), this workflow starts by casting all data to single polygons first. Then, the polygons are repaired using *sf::st_make_valid* (Pebesma, 2018; Pebesma and Bivand, 2023), which splits self-intersecting polygons into non overlapping, individual parts. Retaining all covered areas, this approach solves all topological errors illustrated in Fig. S1, except incomplete geometries (cf. S1 d). Here, as previously mentioned, a manual topology inspection using FME was necessary.

2.3. Compilation of a unified dataset

Since, for downstream applications, the noise exposure levels should be assigned to health data (Wolf et al., 2023), we aimed to compile a single, user-friendly and nation-wide record. Thus, next, the individual repaired input files were merged and the features sorted by their L_{den}

[4] https://www.datakustik.com/products/cadnaa/cadnaa.

[5] https://www.soundplan.eu/de/software/soundplannoise/.

[6] https://www.immi.eu/en/applications.html.

[7] https://pro.arcgis.com/en/pro-app/2.9/tool-reference/conversion/raster-to-polygon.htm.

[8] https://www.zensus2011.de.

[9] https://sg.geodatenzentrum.de/web_public/gdz/dokumentation/deu/LoD1-DE.pdf.

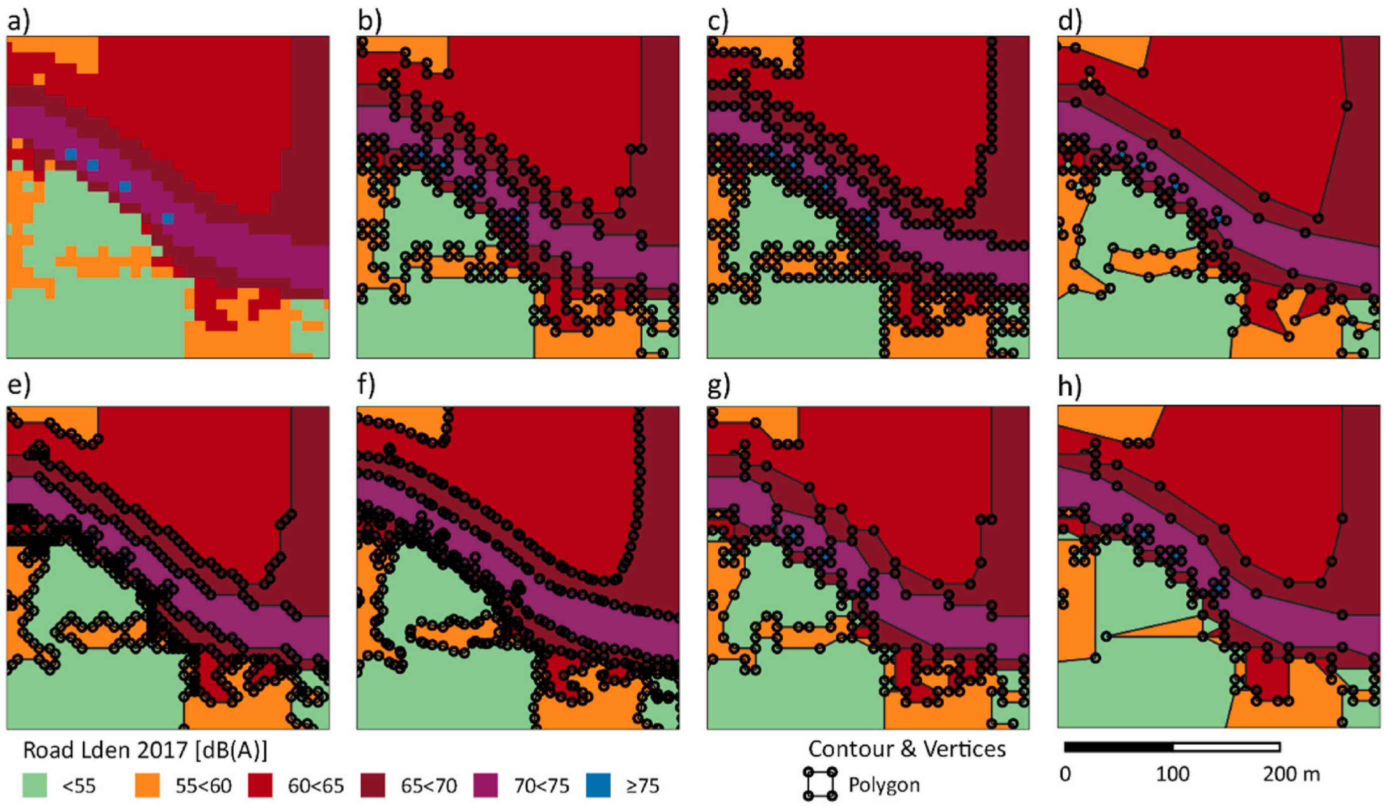

Fig. 2. Results of different raster to polygon conversion applications to the Koblenz dataset. (a) Original raster file. (b) Polygonised raster blocks as generated equally with ArcGIS Pro *Raster to Polygon*, GDAL *Polygonize*, GRASS *r.to.vect* or (c) the R function raster*rasterToPolygons followed by raster:: disaggregate*. For comparability, the vertices are highlighted as dots. Methods (d) ArcGIS Pro *Raster to Polygon* with opted-in simplification, (e) GRASS *r.to.vect* with smoothing corners of area features and (f) GDAL tool *Contour Polygons* with inherent ad-hoc generalization. Analog, polygonised raster blocks (as in b) can be post-processed with ArcGIS Pro *Simplify Polygons retaining critical bends* (Z. Wang and Müller, 1998) *at* different simplification tolerances of (g) 20m and (h) 100m, respectively.

values. This is crucial, as for example along administrative borders, different objects with discordant noise data values can overlap (cf. Fig. S1-k). In such cases, the loudest noise value was considered in favor of the potentially impacted population.

Last, we converted the data to a 10 x 10 Meter, INSPIRE conform raster dataset and assessed the fraction, by which the data volume is decreased just by switching the data format. Although we are aware of a potential loss in detail below the 10 x 10 Meter scale, we argue that raster data is more suitable for spatial analysis. Specifically, pixel values can easily be extracted when mapping the data to national health cohorts or similar further applications. Moreover, this step allows to assign distinct background values, as different minimal mapping units are applied for between urban agglomerations and peripheral areas within the two END obligations. Therefore, the absence of polygons with $L_{den} \geq$ 55 dB (A), legally have different semantic meanings. In those areas scoped with noise reports for urban agglomerations (END Article 3 section *k*), in theory, all roads should be mapped – including small and quiet ones. Within the respective administrative boundaries, we assigned the digital number 253 as background value. Akin to a lower dB (A) threshold recommended by Riedel et al. (2018), users may manually reassign these pixels to their needs. Vice versa, the large areal proportions unaffected by noise emitted from major roads with more than 3 million vehicles passing per year (END Article 3 section *n*) may potentially still exceed critical noise levels due to other busy roads. For provenance reasons, we have set to the digital number of these areas to 254. Beyond the German landmass territory, the number 255 was assigned (which was also set as the NA-value of the GeoTiff).

2.4. Zonal statistics

Complementary to the officially reported number of exposed inhabitants[10], we assessed the affected areas from a geographical perspective. We summarized the affected areas per noise band on a national scale first. In further detail, a comparison of areas covered by the two distinct mapping obligations for urban agglomerations and major roads (END Article 3 Sections *k* and *n*), is presented as well. We thereby distinguish low and highly populated areas below and above a threshold of 10 inhabitants per 100 x 100 Meter census grid cell. This bifurcation threshold is set analog to the German density threshold of 1000 inhabitants per square kilometer defined by the BImSchG §47b.3 for reference.

3. Results

3.1. Conversion biases

Having converted the original 10 x 10 Meter raster noise map provided by the city of Koblenz to polygons using different algorithms and settings, nine datasets were produced. A visual comparison of raster data (Fig. 2a) against polygon representations (Fig. 2b–h) shows, that variations exist on two scopes – number of vertices and geometrical shape. Inspecting the most basic operation, generating polygons along the raster pixels without simplification (Fig. 2b–c), some implementations store relevant vertices at corners only, while the *R* function includes

[10] https://www.eea.europa.eu/themes/human/noise/noise-fact-sheets/noise-country-fact-sheets-2021/germany.

Table 2
Zonal aggregate of exposed population per L_{den} noise band exemplified for the original raster reference dataset of Koblenz being converted using different raster to polygon methods. First row shows absolute number based on original raster reference, while for the a-priori converted inputs the deviation of respectively exposed inhabitant per noise band is presented.

L_{den} dB(A)	55 - < 60	60 - < 65	65 - < 70	70 - <75	≥75
Absolute Number of Exposed Population in Koblenz Reference Raster	12,978	10,937	5123	542	26
Conversion Method	**Absolute Deviation (Relative Deviation in %)**				
ArcGIS Pro *Raster to Polygon* (b)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
GDAL *Polygonize* (b)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
GRASS *r.to.vect* (b)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
R *rasterToPolygons* (c)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
ArcGIS Pro *RastertoPolygon* Simplified (d)	−234 (−1.8)	−130 (−1.2)	+52 (1.0)	+15 (2.8)	0 (0.0)
GRASS *r.to.vect* Smoothed (e)	−33 (−0.3)	−46 (−0.4)	−38 (−0.7)	+3 (0.6)	0 (0.0)
GDAL *Contour Polygons* (f)	+72 (0.6)	+260 (2.4)	−723 (−14.1)	−211 (−38.9)	−23 (−88.5)
ArcGIS Pro *Raster to Polygon* + ArcGIS Pro *Simplify* Bend 20m (g)	−409 (−3.2)	−458 (−4.2)	−35 (−0.7)	+32 (5.9)	+26 (100.0)
ArcGIS Pro *Raster to Polygon* + ArcGIS Pro *Simplify* Bend 100m (h)	−1129 (−8.7)	−766 (−7.0)	−15 (−0.3)	+180 (33.2)	+26 (100.0)

dispensable vertices along straight lines (which can be removed in a post processing step suggested in the respective documentation). By reducing the number of stored vertices further, the shapes generalize – also referred to as smoothing or simplification. The course of edges is altered and particular small patches of high noise levels above 75 dB(A) tend to be decreased in size or even vanish. When the polygon simplification was performed on pixel-based conversions post-hoc using the generalization tool *Simplify Polygons in* ArcGIS Pro (Z. Wang and Müller, 1998), the layout changes yet again. The geometries depict in Fig. 2g–h appear chiseled, with a mix of rectangular and triangular shapes.

The visual impressions are backed by empiric shape metrics (c.f. Supplementary Table S4). Considering the pixelated approaches first, the contour length per enclosed area is – as expected – equal across all implementations. The number of vertices relative to the enclosed area, however, slightly varies and stands out significantly when using the R function *raster::rasterToPolygons* (c). When compared to the other, generalizing, raster to polygon implementations' outputs, the contour per area is decreased for all methods but GRASS *r.to.vect* (b). Regarding the hosting of such environmental exposure data online, it is relevant to mention, that the respective reduction of vertices decreases the data volume and archiving costs. Relative to the contour length, the number of vertices deviates in two directions compared to the pixelated outputs as reference. The round appearing outputs from GDAL *Contour Polygons* (f) and GRASS *r.to.vect* with smoothing (e) have a higher ratio of vertices than the other algorithms' outputs appearing chiseled.

Similar to shape metrics, the number of exposed persons differs depending on the conversion method, too, except for pixelated ones (Table 2). Aggregated across all noise bands, the total number of concerned persons generally is decreased. With 114 persons, this effect is the least pronounced with smoothing opted-in GRASS *r.to.vect* (e) but becomes stronger for the other generalizing approaches. In further detail, a second bias is apparent - the distributions across the noise bands change. In particular, the number of exposed persons to noise levels above 70 dB(A) is altered. These deviations are strongest for post-hoc generalizations applied with ArcMap *Simplify* retaining critical bends with a simplification tolerance of 20m (g) or 100 m (h) to ArcMap *RastertoPolygon*, where – in the last two tabular rows - the number of highly exposed people is even doubled. In contrast, using the *ContourPolgyons* tool from GDAL reduces the number of highly exposed population.

Table 3
Spatial aggregations of areas (in %) exposed to road traffic noise per L_{den} noise band in Germany. Split according to the two sections END Article 3, the statistics distinguish urban agglomerations (Sec. *k*) and other areas only concerned by major roads (Sec. *n*) respectively. The columns are further separated by low- and high population density, referring to a threshold of 1000 inhabitants per square kilometer.

L_{den} dB (A)	Germany	Urban Agglomerations (Sec. *k*)		Major Roads (Sec. *n*)	
		Low Pop. Dens.	High Pop. Dens.	Low Pop. Dens.	High Pop. Dens.
≥75	0.39 %	2.28 %	1.09 %	0.35 %	0.12 %
70 < 75	0.50 %	2.89 %	3.76 %	0.39 %	0.63 %
65 < 70	0.95 %	5.52 %	6.21 %	0.78 %	0.88 %
60 < 65	1.77 %	9.34 %	8.63 %	1.51 %	1.52 %
55 < 60	3.04 %	14.33 %	14.13 %	2.58 %	3.85 %
<55	2.27 %	65.63 %	66.17 %	–	–
NoData	91.08 %	–	–	94.4 %	93 %
Total Area	357,690 km^2	8988 km^2	3363 km^2	329,432 km^2	15,906 km^2

3.2. Input data assessment

It was already shown in Table 1, that the data obtained from the EEA's data repository feature varied metadata. But also, the legacy of each file – being initially a raster output of an engineers' noise simulation and converted to polygonal maps later – has left geometric artifacts in the respective shapefile organization of vertices. These were assessed in two ways: by manual interpreting the map, and empirically using shape metrics. As visualized in Fig. 3, the number of vertices and the contour length follow non-random distributions along the diagonal ratio of both. In fact, these clusters correlate to the manual geometric assessment. High spatial resolution datasets, shown in red, have significantly more vertices per area. The number of vertices relative to the contour length delineates a disjunct threshold of 0.04 vertices per m^2 for ~1 Meter datasets, while a ratio of less than 0.02 corresponds to ~10 Meter data. Interestingly, the manually hard to scrutinize cases for the cities Dortmund, Hagen and Essen are interjacent, align to Bochum manually gauged as ~5 Meter resolution. Within the point clouds confidently classified as ~1 (red) and ~10 Meter resolution (green), the decreasing order of *contoured* shapes (circles) having steeper diagonal trends compared to *pixelated* (squares) and *chiseled* (triangles) datasets is repeated. Depicted with filled icons, datasets for urban agglomerations (Section *k* of END Article 3) tend to exhibit longer contour lengths per circumventing area [m/m^2]. The values are plausible, as noise reports here cover more complex structures with fine details on proportionally compact areas.

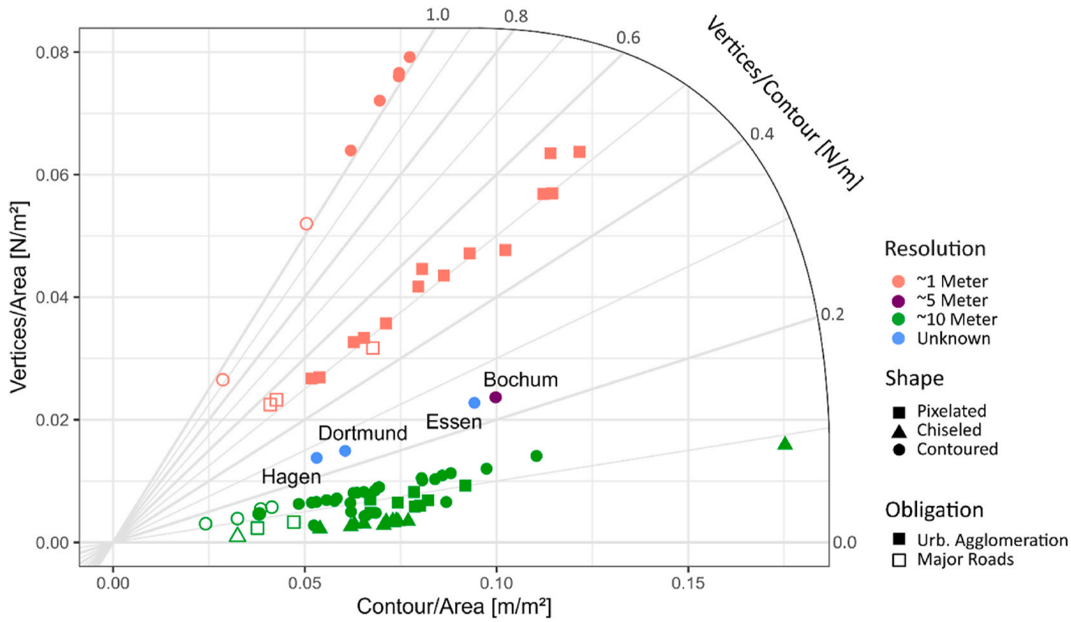

Fig. 3. Shape metrics describing geometric properties of all 2017 L_{den} noise maps in Germany. X and Y axis denote contour length [m] and vertices count [N] per area [m^2], while diagonal grid lines delineate the ratio of vertices per contour length [N/m]. The observable details in the noise map data are represented using a three-dimensional symbology. Colors delineate the approximated spatial resolution, the icons refer to three distinguished geometric shape families, while the filling of the icons point out the respective sections in Article 3 of the END (*k* for roads in urban agglomerations and *n* for noise mapped along major roads. Three trends emerge. First, the observations cluster along diagonal grid lines. Second, a distinct clustering exists between red with high vertex per contour length ratios opposed to blue and green points. Third, hollow icons tend to show less contour length per area [m/m^2] versus filled ones. Tabular representation of data available in S5.

3.3. Unified national dataset

After combining the topologically corrected road traffic noise maps and cropping them to the administrative boundary of Germany,[11] the unified file contains information on the overall 357,689 km^2 of landmass territory. Fig. 4 shows the nationwide road L_{den} values for Germany in 2017. For urban agglomerations (END Article 3 section *k*), the high spatial and semantic resolution of the strategic noise maps are illustrated. Exemplarily shown with parts of the federal city state of Hamburg (Fig. 4b left, annotated as DE_f_ag1), as well as with the extended urban agglomeration north of Hamburg (Fig. 4b right, annotated as DE_f_ag1N), strategic noise maps for urban agglomerations show significant details in populated areas (grey hatched background). Complemented by the other section, *n* of END Article 3, these highly exposed areas are distributed along the federal highway network with narrow and most often short dendrites along regional highways areas (Fig. 4c). In detail though, the reported noise maps do not always integrate seamlessly. While this is generally true due to different minimum mapping units for urban agglomerations and their surrounding areas, also in detail, inconsistent noise simulation outputs can be observed along individual road segments. Fig. 4d showcases a significant contrast along the shared administrative boundary of the two federal states Baden-Württemberg and Hesse - most probably originating from given degrees of freedom in the underlying Good Practice Guide (WG-AEN, 2007) and traffic surveys recommendations (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012).

After being cropped to the administrative boundary of Germany, the raster with a 10 x 10 Meter resolution (EPSG:3035) contains approximately 3.6 billion analysis-ready pixels. The file, available for download,[12] was stored as DEFLATE compressed 8-Bit, cloud-optimized GeoTiff and scopes only a data volume of 77.9 MB. Compared to the original inputs this is a reduction in size of 97 %.

[11] https://daten.gdz.bkg.bund.de/produkte/dlm/dlm250/2017/.
[12] https://doi.org/10.15489/a6wg11lrub77

3.4. Zonal statistics

Aggregated statistics, as shown in Table 3, reinforce the visual observation that the largest part of Germany, covering 93.35 % of its area, is exposed to road traffic noise L_{den} values either below 55 dB(A) or is not subject to the relevant mapping obligation (NoData). Vice versa, critical noise levels above 55 dB affect 6.65 % of the total area. Distinguishing between the two sections *k* and *n* of the END Article 3, however, emphasizes that critical noise levels are more common in urban agglomerations.

When considering the population density, the proportions of affected areas are close within each obligation for all noise bands, but very high road traffic noise levels above 75 dB(A) L_{den}. Here a significant drop is measured in high populated areas.

4. Discussion

Among other stressors, noise pollution is known to have negative health impacts as well as to contribute to a decrease in overall quality of life for people living in affected areas. In this context, European efforts in noise mapping are the basis for local noise strategy development. But can it be used to evaluate and compare exposed areas and populations in national analyses? Despite the clear usefulness, the END and its resulting data have been subject to critical review ever since its introduction. The implementation of the Directive and its incorporation into governance structures was found to be challenging (Stimac, 2005). In the very same year it was noted by Nijland and Van Wee (2005), that comparing data across various constituencies posed challenges due to different national calculation methods and noise indices. More recently, Khomenko et al. (2022) found different data formats and reporting qualities across Europe. In this paper, where German noise contour maps were examined in further detail, we could reveal differences in the granularity of mapped polygon data across regions as well as significant deviations from OGC standards for geographic data. Thereby, a deep excursion into the geospatial data storing structures and different implementations of standard GIS tools was made to illustrate that the selection of algorithms

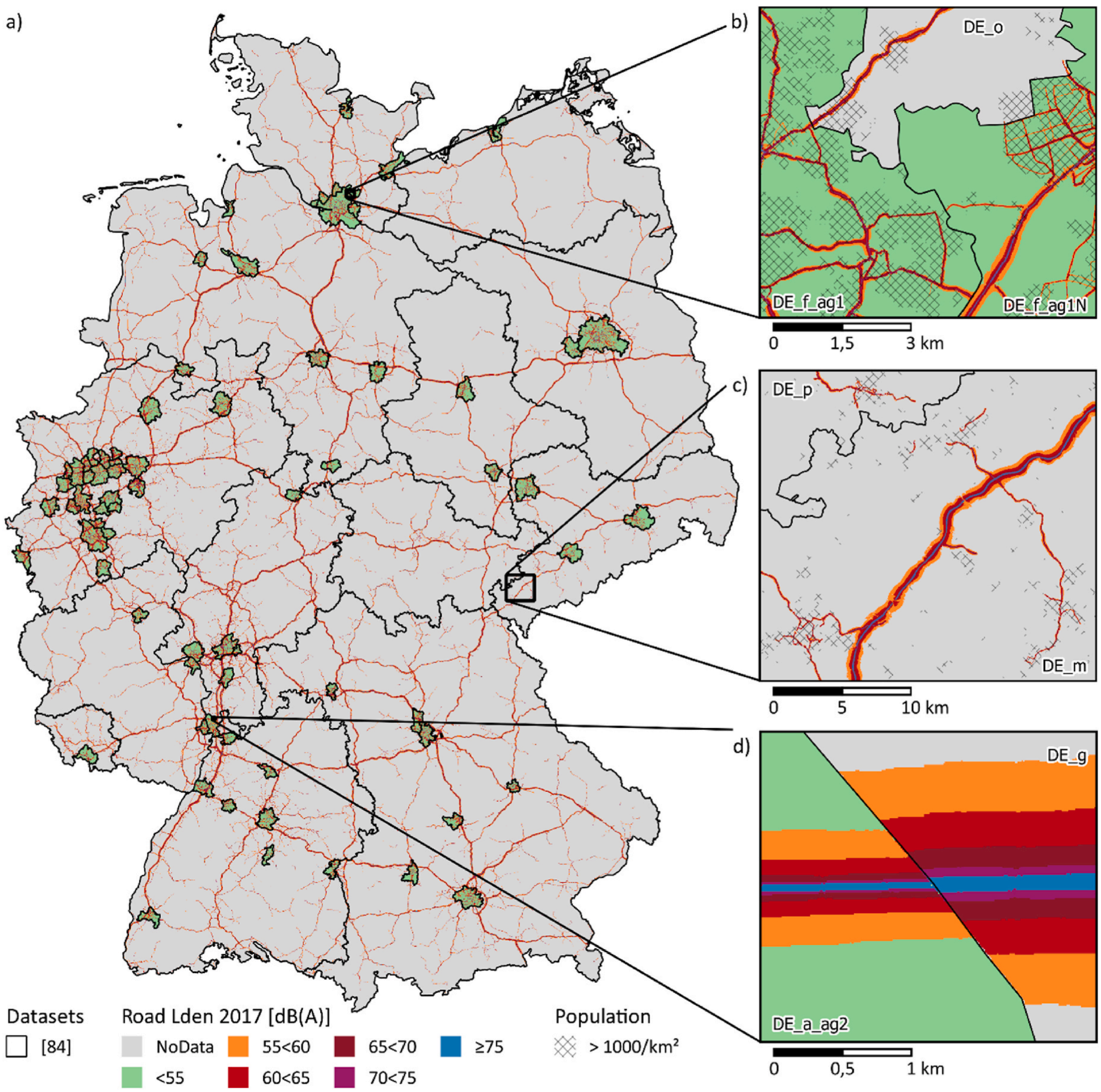

Fig. 4. a) Nationwide raster at 10 Meter resolution. Subplots show information for b) the larger urban agglomerations mapped around Hamburg with areas exposed to noise levels above 55 dB(A) and c) a peripheral area where most noise is only mapped along major roads. Example d) illustrates contradicting values along administrative borders. Color scheme akin to DIN 18005, showing merged 2017 strategic noise maps downloaded via the central data repository of the European Environment Agency. Grey outline depicts extent of original input data files having reported the noise maps under the obligations of the Environmental Noise Directive 2002/49/EC, the printed file names can be found in S5 for reference. Hatched areas highlight population densities above 1,000 inhabitants per square kilometer.

used for converting the engineers' output into noise contour maps has qualitative impacts. Thereby, three groups of tools were identified, each leading to distinct visual impression and a respective ratio of vertices per contour length needed to circumvent critically loud areas.

This paper therefore serves as thorough assessment of the 2017 road L_{den} dataset for Germany. For subsequent utilizations, such as national exposure assessments, it is relevant to have documented regional variations. Fig. 3 and its respective tabular representation supplementary Table S5 highlight heterogeneous input data granularities. As illustrated for our exemplary test site Koblenz in Table 2, the different post-processing methods applied to convert raster to polygon data, potentially affects the exposure assessment. Our experiment showed, that in particular the two contouring approaches with round and organic-seeming shapes distort the number of exposed people. In fact, however, the majority of the investigated data sets were interpreted as generalized using such an approach (43 of 84, referring to S5). From an inductive point of view, users of the data should be aware of the associated uncertainties when working within these regions. With this, our work aims to aid in both, the development of sustainable transportation policies, as well as a thoroughly documented data basis for health cohort studies analyzing noise pollution (e.g. Zijlema et al., 2016; Wolf et al., 2023).

Methodically, however, our work leaves some gaps: First, only road traffic L_{den} data was assessed. The unification workflow is suggested to be applied to other noise emitting sources (e.g. railways, airport and industry) in the future, as well as to for example nighttime indicators (L_{night}). In the latter context, it may be noted that beyond END reports (D. Khan and Burdzik, 2023), other indicators describing short term noise and qualifying soundscapes in general are known to be health relevant (Karipidis et al., 2014; Riedel et al., 2015; Aletta et al., 2018; Skånberg and Öhrström, 2002; Chen et al., 2024), whereby the geocoding problems described in this study apply to respective maps even so. Second, an inductive approach was taken, using the local dataset of Koblenz to thoroughly investigate geometric artifacts introduced by different conversion algorithms. Transferring this knowledge to the 83 other input datasets, we have shown inconsistent data properties across German noise reports. The presented findings may be transferred to other regions in Europe reporting noise contours using polygonal vector data. But also, expanding this methodical design, future studies might adopt the concept to other data types such as line strings common in Europe, too (Khomenko et al., 2022). Along this documentation, we developed a workflow for fixing topological errors using a reference dataset (c.f. supplementary Fig. S1). However, we could only clean the data - areas for which no or generalized data is present, stayed unaltered. For example, we were unable to level contradicting values along administrative borders (c.f. Fig. 4d). As both, the underlying Good Practice Guide (WG-AEN, 2007) and the German recommendations for traffic surveys (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012) leave some degrees of freedom with respect to input data, such that contradicting values may originate from traffic flow counts conducted on different census days, distinct parametrization within the complex noise simulation or utilization of different software suites. In favor of the potentially affected population, we have chosen the cases of highest values, where multiple reports overlapped spatially. But, with respect to direct comparisons across different strategic noise maps needs, we encourage future studies to consider this carefully. Future mapping rounds, however, shall use the CNOSSOS-EU noise indicator which intends to resolve comparability issues and is known to depict the real noise situation more accurately (Faulkner and Murphy, 2022). Moreover, the subplots in Fig. 4 have also shown an information decline along the urban-rural gradient. As all over Germany almost 50 % of the population live on only 1.9 % of the landmass area (Taubenböck et al., 2022), the END's focus of highly concerned areas is very cost efficient per capita. In fact, both – the exceptional noise report for suburban areas north of Hamburg and the few highly populated areas assigned critical values along major roads in Table 3 – allow the hypothesis, that further morphologically urbanized areas (Taubenböck et al., 2019) have critical noise levels as well. Without the future extension of END Article 3 section *k*, such suburban neighborhoods are not delineated. With respect to environmental health assessments, the potential exposed population is underrepresented in these territories. Also, inconsistent noise simulation outputs, such as exemplary highlighted in Fig. 4d, would benefit from a large-scale approach using consistent data inputs and methods. Therefore, we want to urge towards large-scale and cost-efficient noise mapping approaches leveling the mapping standards and filling in existing data gaps. This could be achieved through optimizing the noise calculation methods (H. Wang et al., 2017; Yoo et al., 2024) or using Land-Use-Regressions (D. Xie et al., 2011; Aguilera et al., 2015; Staab et al., 2022), Random Forests (Liu et al., 2020; Singh et al., 2016) and Deep-Learning methods (Eicher et al., 2022; Staab et al., 2023). Such geostatistical approaches leverage the growing availability of satellite- and other geodata (e.g. on traffic volume, speed limits, or build-up structures) in combination with machine learning methods in order to approximate local noise exposures (Weigand et al., 2019). In future studies, both, these advanced calculation methods techniques and the geostatistical approaches may solve the remaining issues. Where, first an improvement towards lower noise bands and the dissolvement of 5 dB intervals is needed (e.g. Staab et al., 2022; Eicher et al., 2022), and second very large-scale, national, continental or even global datasets are needed by the scientific community as well in order to assess the burden of disease (Ögren, 2021; World Health Organization, 2011; Weigand et al., 2019) and to manage the environment holistically (Keyel et al., 2018) eventually. That said, low-cost distributed sensor networks (Vidaña-Vila et al., 2020; Karges et al., 2022) and citizen science approaches measuring the acoustical landscape with smartphone apps in-situ (Radicchi et al., 2016; Murphy and King, 2016) could be used, to in-fill data gaps, complement the simulations, or train geostatistical approaches discussed above.

The aim of this study was to investigate whether the federal reporting system introduces variance beyond the otherwise strictly regulated framework of the END. Our analysis suggests that structural inconsistencies – such as the varying geometric properties of reported noise contours (see Fig. 3) – do in fact reflect underlying heterogeneity in national implementation practices. At the end of 2021, the EEA published reporting guidelines (see Blanes et al., 2021), which include some recommendations on spatial harmonization when building noise contours in future mapping rounds. Although there are some legally binding specifications where countries have to adhere, there are still some vague aspects (i.e. concerning the raster to polygon conversion). In this context, the shape metrics introduced in this study could contribute to an automatic assessment of geometric properties. Opposed to the manual assessment, where it is difficult to assign distinct labels (blue and purple points in aligning in Fig. 3) and the result is subject to the interpreter's concentration as well (c.f. Kraff et al., 2020), these metrics are objective, reproducible and easy to compute. In particular, the number of vertices per contour length [N/m] has emerged as measure to indicate the data's geometric properties. To repository managers receiving data – i.e. the EEA in this concern – we propose to use this easy to implement (see example S6) metric for automated quality assessments. With respect to Europe's ongoing efforts towards a healthier environment, the ultimate goal must be to improve transparency, comparability, and trust in future environmental noise reporting.

5. Conclusions

In this study, we reviewed road traffic noise maps reported to the EEA under the END and their suitability as an input for environmental assessments and other related studies (Faure et al., 2024; Wolf et al. 2023, 2025; Voss et al., 2021; Szczepańska et al., 2020; Lakes et al., 2013; Niedermayer et al., 2025). After Khomenko et al. (2022) found different data formats and semantic qualities being common at the European scale, we focused on the technical details of polygon data in particular to show, that algorithm choice of a common geodata management task directly biases eventual environmental impact assessments. A long thereto, the technical revision of reported strategic noise maps in Germany scoped a broad band of output resolutions – from pixels, chisels and contours, at ~1, ~5 and ~10 Meter resolution.

Consolidating all 2017 strategic noise maps for Germany, 83 polygonal noise maps were obtained via the EEAs EIONET platform together with one raw simulation noise output file from the city administration of Koblenz. This original ASCII raster file allowed us to reproduce different possible processing workflows of respective data, from federal contractor to user. We could demonstrate that geometric artifacts are produced when converting raster data to polygons using different algorithms available in common software suites. In particular, generalizing the noise maps geometry is subject to the individual settings and implementations. The intention of graphically enhancing the maps and saving data volume by opting-in simplification, smoothing or any other generalizing raster to polygon implementation comes at the costs of losing small details such as local noise hot spots. We demonstrated that, this potentially alters exposure assessments. As such, the generalized data could potentially affect respective noise action planning, too. A resolution of ~5 or ~10 Meter might be insufficient to determine accurate sound propagation in some circumstances (WG-AEN, 2007). Quantified through shape metrics, geometric artifacts such as spatial resolution and level of generalization – could be traced back in the federal datasets. The Supplementary Table S5 documents the inputs of our national 10 x 10 Meter analysis-ready dataset in this very detail and enables users to gauge the local certainty. Users of the dataset must furthermore carefully consider how to interpret the ordinally scaled data as well. In particular, when investigating the absence of road traffic noise, attention must be paid to the different semantic meanings of background values within urban agglomerations (code 253) and other areas (code 254). The unified L_{den} dataset for Germany covers a diverse set of urbanized regions – including the largest cities and even some suburban regions around Hamburg– and peripheral areas affected by critical noise levels emitted from major roads interconnecting the central European homes and industries.

From the results of this study, and for facilitating environmental health analyses, the END directive would benefit from more strict spatial data requirements in noise contour maps that would improve robustness and interoperability of the data. As the European spatial data infrastructures for environmental data are continuously evolving (Abramic et al., 2017), future noise mapping rounds should profit from a more comparable and harmonized methodology for calculating noise (i.e. CNOSSOS-EU) and a newly implemented decision form (2021/1967/EC), that makes a legal requirement to provide noise spatial compliant to the INSPIRE directive. With respect to the very details, however, we like to furthermore discourage stakeholders to post-process the high-quality noise maps. Instead, we recommend publishing the original raster files or, if necessary, pixelated vector data where the polygons conform to the raster's cell edges - as for example, the R function raster*rasterToPolygons followed by raster::disaggregate*. Only then, the very local nature of noise, as it was depicted using labor intense data acquisition, acoustical expertise and dedicated engineering software, is preserved. As a consequence, the valuable data can contribute beyond European reporting obligations to large-scale health, housing and environmental impact assessments.

CRediT authorship contribution statement

Jeroen Staab: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ariane Droin:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. **Matthias Weigand:** Writing – original draft, Software, Resources, Investigation, Formal analysis. **Marco Dallavalle:** Writing – review & editing, Validation, Methodology, Funding acquisition, Data curation. **Kathrin Wolf:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Arthur Schady:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Tobia Lakes:** Writing – review & editing, Supervision, Investigation, Formal analysis. **Michael Wurm:** Writing – review & editing, Resources, Formal analysis. **Hannes Taubenböck:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Software

The utilized software (and versions) in this study are ArcGIS Pro (2.9.0), QGis (3.16.5), FME (2021.2.2.0), Gdal (3.2.1), GRASS (7.8.2), and R (4.1.1) with raster-package (3.5–15).

Declaration of competing interest

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

Acknowledgments

Noise data for roads were obtained from the 2017 Strategic Noise Maps reported under the obligations of the Environmental Noise Directive 2002/49/EC (END). These data were downloaded from the central data repository of the European Environment Agency (EEA). Further we would like to thank the City of Koblenz for providing their original noise simulation data. We extend our appreciation to the German Federal Environmental Foundation (DBU, funding code 20017/500) and Helmholtz Association (Helmholtz Association's Initiative and Networking Fund, funding code ZT-I-PF-5-42 - Noise2NAKO^{AI} Project) for their generous funding support. We express our sincere gratitude to Eulalia Peris from the EEA for providing information about the END, the EEA data repository and her valuable input for improving the work on the datasets. Also, we want to honor Matthias Schultheiss, Nils Karges, Tobias Berning and Ehal Baggio Lorenz for their support of this study. Last but not least, we would like to express our sincere gratitude to the editor and the three anonymous reviewers for their insightful comments, constructive feedback, and valuable suggestions, which have significantly improved the quality and clarity of this work. We deeply appreciate their time and effort in reviewing this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125475.

Data availability

https://doi.org/10.15489/a6wg11lrub77

References

1967/EC, 2021. Decision Setting up a Mandatory Data Repository and a Mandatory Digital Information Exchange Mechanism in Accordance with Directive 2002/49/EC of the European Parliament and of the Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021D1967.

2002/49/EC, 2002. European Noise Directive. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32002L0049.

2007/2/EC, 2007. Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 Establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=uriserv:OJ.L_.2007.108.01.0001.01.DEU.

Abramic, Andrej, Kotsev, Alexander, Cetl, Vlado, Kephalopoulos, Stylianos, Paviotti, Marco, 2017. A spatial data infrastructure for environmental noise data in Europe. Int. J. Environ. Res. Publ. Health 14 (7), 726. https://doi.org/10.3390/ijerph14070726.

Aguilera, Inmaculada, Foraster, Maria, Basagaña, Xavier, Corradi, Elisabetta, Deltell, Alexandre, Morelli, Xavier, Phuleria, Harish C., et al., 2015. Application of land use regression modelling to assess the spatial distribution of road traffic noise in three European cities. J. Expo. Sci. Environ. Epidemiol. 25 (1), 97–105. https://doi.org/10.1038/jes.2014.61.

Aletta, Francesco, Oberman, Tin, Kang, Jian, 2018. Associations between positive health-related effects and soundscapes perceptual constructs: a systematic review. Int. J. Environ. Res. Publ. Health 15 (11), 2392. https://doi.org/10.3390/ijerph15112392.

Angel, Shlomo, Parent, Jason, Civco, Daniel L., 2010. Ten compactness properties of circles: measuring shape in geography. Canadian Geographies/Géographies Canadiennes 54 (4), 441–461. https://doi.org/10.1111/j.1541-0064.2009.00304.x.

Badpa, Mahnaz, Schneider, Alexandra, Schwettmann, Lars, Thorand, Barbara, Wolf, Kathrin, Peters, Annette, 2024. Air pollution, traffic noise, greenness, and temperature and the risk of incident type 2 diabetes: results from the KORA cohort study. Environmental Epidemiology 8 (2), e302. https://doi.org/10.1097/EE9.0000000000000302.

Barr, Jason, Cohen, Jeffrey P., 2014. The floor area ratio gradient: New York city, 1890–2009. Reg. Sci. Urban Econ. 48 (September), 110–119. https://doi.org/10.1016/j.regsciurbeco.2014.03.004.

Basner, Mathias, McGuire, Sarah, 2018. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and effects on sleep. Int. J. Environ. Res. Publ. Health 15 (3), 519. https://doi.org/10.3390/ijerph15030519.

Bhatia, Rajiv, Seto, Edmund, 2011. Quantitative estimation in health impact assessment: opportunities and challenges. Environ. Impact Assess. Rev. 31 (3), 301–309. https://doi.org/10.1016/j.eiar.2010.08.003.

Blanes, Núria, Closa, Guillem, José Ramos, Maria, Sáinz de la Maza, Miquel, Peris, Eulàlia, Lihteneger, Darja, 2021. Environmental noise directive reporting guidelines - DF4_8 strategic noise maps. https://www.eionet.europa.eu/reportnet/docs/noise/guidelines/reportingguidelines_df4_8_strategicnoisemaps_december2021.pdf/.

Brink, Mark, Schäffer, Beat, Pieren, Reto, Wunderli, Jean Marc, 2018. Conversion between noise exposure indicators Leq 24h , L Day , L evening , L night , L Dn and L den : Principles and practical guidance. Int. J. Hyg Environ. Health 221 (1), 54–63. https://doi.org/10.1016/j.ijheh.2017.10.003.

Animal communication and noise. In: Brumm, Henrik (Ed.), 2013. Animal Signals and Communication, vol. 2. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-41494-7.

Buxton, Rachel T., McKenna, Megan F., Mennitt, Daniel, Fristrup, Kurt, Crooks, Kevin, Angeloni, Lisa, George, Wittemyer, 2017. Noise pollution is pervasive in US protected areas. Science 356 (6337), 531–533.

Camerin, Federico, Longato, Davide, 2024. Designing healthier cities to improve life quality: unveiling challenges and outcomes in two Spanish cases. Journal of Urban Design, May. https://doi.org/10.1080/13574809.2024.2351925.
Chen, Zhu, Hermes, Johannes, Von Haaren, Christina, 2024. Mapping and assessing natural soundscape quality: an indicator-based model for landscape planning. J. Environ. Manag. 354 (March), 120422. https://doi.org/10.1016/j.jenvman.2024.120422.
Clark, Charlotte, Paunovic, Katarina, 2018. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cognition. Int. J. Environ. Res. Publ. Health 15 (2), 285. https://doi.org/10.3390/ijerph15020285.
Congalton, Russell, 1997. Exploring and evaluating the consequences of vector-to-raster and raster-to-vector conversion. Photogramm. Eng. Rem. Sens. 63 (April), 425–434.
Eicher, Leonardo, Mommert, Michael, Borth, Damian, 2022. Traffic noise estimation from satellite imagery with deep learning. In: IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium. Kuala Lumpur, Malaysia: IEEE, pp. 5937–5940. https://doi.org/10.1109/IGARSS46834.2022.9883463.
Eriksson, Charlotta, Nilsson, Mats E., Stenkvist, Dag, Bellander, Tom, Pershagen, Göran, 2013. Residential traffic noise exposure assessment: application and evaluation of European environmental noise directive maps. J. Expo. Sci. Environ. Epidemiol. 23 (5), 531–538. https://doi.org/10.1038/jes.2012.60.
European Environment Agency, 2020. Environmental Noise in Europe - 2020. Publications Office, LU. https://data.europa.eu/doi/10.2800/686249.
European Environment Agency, 2021. EEA-eionet Strategy 2021-2030, LU. Publications Office. https://data.europa.eu/doi/10.2800/92395.
Faulkner, Jon-Paul, Murphy, Enda, 2022. Road traffic noise modelling and population exposure estimation using CNOSSOS-EU: insights from Ireland. Appl. Acoust. 192 (April), 108692. https://doi.org/10.1016/j.apacoust.2022.108692.
Faure, E., Houeto, A., Boileau, A., Perrin, C., Gelot, A., Correia, E., Artaud, F., et al., 2024. Association between transportation noise exposure ans hypertension risk in the French E3N cohort. In: Proceedings of the 10th Convention of the European Acoustics Association Forum Acusticum 2023, pp. 4651–4654. https://doi.org/10.61782/fa.2023.0789. Turin, Italy: European Acoustics Association.
Federal Immission Control Act - BImSchG, 1974. Act on the protection against harmful environmental effects caused by air pollution, noise, vibrations, and similar processes. https://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_26081998_IG19980826.htm.
Federal Ministry of Transport and Digital Infrastructure. 1990. "Guidelines for Noise Protection on Roads (RLS-90)." Köln 1:7–8.
Fiedler, Paulo Eduardo Kirrian, Zannin, Paulo Henrique Trombetta, 2015. Evaluation of noise pollution in urban traffic hubs—noise maps and measurements. Environ. Impact Assess. Rev. 51 (February), 1–9. https://doi.org/10.1016/j.eiar.2014.09.014.
Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012. In: Recommendations for Traffic Surveys - Empfehlungen für Verkehrserhebungen (EVE). Ausg. 2012. FGSV R2, Regelwerke 125. FGSV-Verl, Köln.
Francis, Clinton D., Kleist, N.J., Ortega, C.P., Cruz, A., 2012. Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. Proc. Biol. Sci. 279 (1739), 2727–2735. https://doi.org/10.1098/rspb.2012.0230.
Francis, Clinton D., Newman, Peter, Derrick Taff, B., White, Crow, Monz, Christopher A., Mitchell, Levenhagen, Petrelli, Alissa R., et al., 2017. Acoustic environments matter: synergistic benefits to humans and ecological communities. J. Environ. Manag. 203 (December), 245–254. https://doi.org/10.1016/j.jenvman.2017.07.041.
Garg, Naveen, Maji, Sagar, 2014. A critical review of principal traffic noise models: strategies and implications. Environ. Impact Assess. Rev. 46, 68–81. https://doi.org/10.1016/j.eiar.2014.02.001.
Geraghty, P.J., 1996. Environmental impact assessment practice in Ireland following the adoption of the European directive. Environ. Impact Assess. Rev. 16 (3), 189–211. https://doi.org/10.1016/0195-9255(96)00049-2.
Gidlöf-Gunnarsson, Anita, Öhrström, Evy, 2007. Noise and well-being in urban residential environments: the potential role of perceived availability to nearby green areas. Landsc. Urban Plann. 83 (2–3), 115–126. https://doi.org/10.1016/j.landurbplan.2007.03.003.
Gu, Tiantian, Yang, Teng, Wang, Jiawei, Hu, Xin, Xu, Zhihu, Wang, Yuxin, Jin, Jianbo, et al., 2023. Modification of green space on the associations between long-term road traffic noise exposure and incident intracerebral hemorrhage: a prospective cohort study. Environ. Res. 231 (August), 116189. https://doi.org/10.1016/j.envres.2023.116189.
Guski, Rainer, Schreckenberg, Dirk, Schuemer, Rudolf, 2017. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and annoyance. Int. J. Environ. Res. Publ. Health 14 (12), 1539. https://doi.org/10.3390/ijerph14121539.
Han, Xiaopeng, Huang, Xin, Liang, Hong, Ma, Song, Gong, Jianya, 2018. Analysis of the relationships between environmental noise and urban morphology. Environ. Pollut. 233, 755–763. https://doi.org/10.1016/j.envpol.2017.10.126.
Herder, Christian, Zhang, Siqi, Wolf, Kathrin, Maalmi, Haifa, Bönhof, Gidon J., Rathmann, Wolfgang, Schwettmann, Lars, et al., 2023. Environmental risk factors of incident distal sensorimotor polyneuropathy: results from the prospective population-based KORA F4/FF4 study. Sci. Total Environ. 858 (February), 159878. https://doi.org/10.1016/j.scitotenv.2022.159878.
Hernández, Rafael Córdoba, Camerin, Federico, 2024. The application of ecosystem assessments in land use planning: a case study for supporting decisions toward ecosystem protection. Futures 161 (August), 103399. https://doi.org/10.1016/j.futures.2024.103399.
Herring, John R., 2011. "OpenGIS® implementation standard for geographic information. Simple Feature Access - Part 1: Common Architecture 93. https://doi.org/10.25607/OBP-630 [Corrigendum].
Huang, Ching-Hsuan, Seto, Edmund, 2024. Estimates of population highly annoyed from transportation noise in the United States: an unfair share of the burden by race and ethnicity. Environ. Impact Assess. Rev. 104 (January), 107338. https://doi.org/10.1016/j.eiar.2023.107338.
Ivanović, Lozica, Josifović, Danica, Ilic, Andreja, Stojanovic, Blaza, Rakic, B., 2014. Noise as aspect of life quality at urban areas. https://scidar.kg.ac.rs/handle/123456789/16912.
Jones, Dylan M., Chapman, Antony J., Auburn, Timothy C., 1981. Noise in the environment: a social perspective. J. Environ. Psychol. 1 (1), 43–59.
Kalisa, Egide, Irankunda, Elisephane, Rugengamanzi, Eulade, Amani, Mabano, 2022. Noise levels associated with urban land use types in kigali, Rwanda. Heliyon 8 (9), e10653. https://doi.org/10.1016/j.heliyon.2022.e10653.
Karges, Nils, Staab, Jeroen, Rauh, Jürgen, Wegmann, Martin, Taubenböck, Hannes, 2022. Soundscapes on edge - the real-time machine learning approach for measuring soundscapes on resource-constrained devices. In: Proceedings of the 24th International Congress on Acoustics. Gyeongju, Korea. https://www.scopus.com/record/display.uri?eid=2-s2.0-85153779648.
Karipidis, Ioannis, Vienneau, Danielle, Habermacher, Manuel, Köpflii, Micha, Brink, Mark, Probst-Hensch, Nicole, Röösli, Martin, Wunderli, Jean-Marc, 2014. Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE Project. Noise Mapp. 1 (1). https://doi.org/10.2478/noise-2014-0002.
Kempen, Elise van, Babisch, Wolfgang, 2012. The quantitative relationship between road traffic noise and hypertension: a meta-analysis. J. Hypertens. 30 (6), 1075–1086. https://doi.org/10.1097/HJH.0b013e328352ac54.
Kephalopoulos, Stylianos, Paviotti, Marco, Anfosso-Lédée, Fabienne, Van Maercke, Dirk, Simon, Shilton, Jones, Nigel, 2014. Advances in the development of common noise assessment methods in Europe: the CNOSSOS-EU framework for strategic environmental noise mapping. Sci. Total Environ. 400–410. https://doi.org/10.1016/j.scitotenv.2014.02.031, 482–483 (June).
Keyel, Alexander C., Reed, Sarah E., Nuessly, Kathryn, Cinto-Mejia, Elizeth, Barber, Jesse R., George, Wittemyer, 2018. Modeling anthropogenic noise impacts on animals in natural areas. Landsc. Urban Plann. 180 (December), 76–84. https://doi.org/10.1016/j.landurbplan.2018.08.011.
Khan, Diyar, Burdzik, Rafał, 2023. A review on different regulation for the measurement of Transport noise and vibration. Journal of Measurements in Engineering 11 (2), 196–213. https://doi.org/10.21595/jme.2023.23279.
Khan, Jibran, Ketzel, Matthias, Kakosimos, Konstantinos, Sørensen, Mette, Jensen, Steen Solvang, 2018. Road traffic air and noise pollution exposure assessment – a review of tools and techniques. Sci. Total Environ. 634 (September), 661–676. https://doi.org/10.1016/j.scitotenv.2018.03.374.
Khan, Jibran, Ketzel, Matthias, Jensen, Steen Solvang, Gulliver, John, Thysell, Erik, Hertel, Ole, 2021. Comparison of road traffic noise prediction models: CNOSSOS-EU, Nord2000 and TRANEX. Environ. Pollut. 270 (February), 116240. https://doi.org/10.1016/j.envpol.2020.116240.
Khomenko, Sasha, Cirach, Marta, Barrera-Gómez, Jose, Pereira-Barboza, Evelise, Iungman, Tamara, Mueller, Natalie, Foraster, Maria, et al., 2022. Impact of road traffic noise on annoyance and preventable mortality in European cities: a health impact assessment. Environ. Int. 162 (April), 107160. https://doi.org/10.1016/j.envint.2022.107160.
King, E.A., Murphy, E., Rice, H.J., 2011. Implementation of the EU environmental noise directive: lessons from the first phase of strategic noise mapping and action planning in Ireland. J. Environ. Manag. 92 (3), 756–764. https://doi.org/10.1016/j.jenvman.2010.10.034.
Kraff, Nicolas Johannes, Wurm, Michael, Taubenböck, Hannes, 2020. Uncertainties of human perception in visual image interpretation in complex urban environments. IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 13, 4229–4241. https://doi.org/10.1109/JSTARS.2020.3011543.
Lakes, Tobia, Brückner, Maria, Krämer, Alexander, 2013. Development of an environmental justice index to determine socio-economic disparities of noise pollution and green space in residential areas in Berlin. J. Environ. Plann. Manag. 57 (4), 538–556. https://doi.org/10.1080/09640568.2012.755461.
Liu, Ying, Goudreau, Sophie, Oiamo, Tor, Rainham, Daniel, Hatzopoulou, Marianne, Chen, Hong, Davies, Hugh, et al., 2020. Comparison of land use regression and random Forests models on estimating noise levels in five Canadian cities. Environ. Pollut. 256 (January), 113367. https://doi.org/10.1016/j.envpol.2019.113367.
Marquet, Oriol, Anguelovski, Isabelle, Nello-Deakin, Samuel, Honey-Rosés, Jordi, 2024. Decoding the 15-minute city debate: conspiracies, Backlash, and dissent in planning for proximity. J. Am. Plann. Assoc. 1–9. https://doi.org/10.1080/01944363.2024.2346596. June.
McMichael, Anthony J., 2000. The urban environment and health in a World of increasing globalization: issues for developing countries. Bull. World Health Organ. 78, 1117–1126. https://doi.org/10.1590/S0042-96862000000900007.
Meller, Gabriela, Magalhães de Lourenço, Willian, Gomes de Melo, Viviane Suzey, Grigoletti, Giane de Campos, 2023. Use of noise prediction models for road noise mapping in locations that do not have a standardized model: a short systematic review. Environ. Monit. Assess. 195 (6), 740. https://doi.org/10.1007/s10661-023-11268-9.
Michaud, David S., Marro, Leonora, Allison, Denning, Shackleton, Shelley, Toutant, Nicolas, McNamee, James P., 2023. Chronic sleep disturbance among adult Canadians: associations and implications to the evaluation of noise impacts under Canada's impact assessment Act. Environ. Impact Assess. Rev. 101 (July), 107109. https://doi.org/10.1016/j.eiar.2023.107109.
Morawetz, Ulrich B., Allen Klaiber, H., Zhao, Hongxi, 2024. The impact of traffic noise on the capitalization of public walking area: a hedonic analysis of Vienna, Austria.

J. Environ. Manag. 353 (February), 120060. https://doi.org/10.1016/j.jenvman.2024.120060.
Murphy, Enda, King, Eoin A., 2016. Smartphone-based noise mapping: integrating sound level meter app data into the strategic noise mapping process. Sci. Total Environ. 562 (August), 852–859. https://doi.org/10.1016/j.scitotenv.2016.04.076.
Murphy, Enda, Owen, Douglas, 2018. Population exposure to road traffic noise: experimental results from varying exposure estimation approaches. Transport. Res. Transport Environ. 58 (January), 70–79. https://doi.org/10.1016/j.trd.2017.11.006.
Murphy, Enda, Jon, Paul Faulkner, Owen, Douglas, 2020. Current state-of-the-art and new directions in strategic environmental noise mapping. Current Pollution Reports 6 (2), 54–64. https://doi.org/10.1007/s40726-020-00141-9.
Niedermayer, Fiona, Rospleszcz, Susanne, Matthiessen, Clara, Hoffmann, Barbara Heidi, Stöcklein, Sophia, Haueise, Tobias, Norajitra, Thanaporn, et al., 2025. "Associations of road traffic noise with adipose tissue depots and hepatic fat content. Results from the German National Cohort (NAKO).
Nijland, H.A., Van Wee, G.P., 2005. Traffic noise in Europe: a comparison of calculation methods, noise indices and noise standards for road and Railroad traffic in Europe. Transp. Rev. 25 (5), 591–612. https://doi.org/10.1080/01441640500115850.
Ögren, Mikael, 2021. Estimating noise exposure for burden of disease calculations in country-sized areas. Stockholm. https://scholar.google.com/citations?view_op=view_citation&hl=de&user=kJV6bCYAAAAJ&sortby=pubdate&citation_for_view=kJV6bCYAAAAJ:LkGwnXOMwfcC.
Open Geospatial Consortium, 2019. OGC GeoTIFF standard. http://www.opengis.net/doc/IS/GeoTIFF/1.1.
Passchier-Vermeer, Willy, Passchier, Wim F., 2000. Noise exposure and public health. Environ. Health Perspect. 108 (Suppl. 1), 123.
Pebesma, Edzer, 2018. Simple features for R: Standardized support for spatial vector data. The R Journal 10 (1), 439. https://doi.org/10.32614/RJ-2018-009.
Pebesma, Edzer, Bivand, Roger, 2023. Spatial Data Science: with Applications in R, first ed. Chapman and Hall/CRC, Boca Raton. https://doi.org/10.1201/9780429459016.
Peters, Annette, Peters, Annette, Halina Greiser, Karin, Göttlicher, Susanne, Ahrens, Wolfgang, Albrecht, Maren, Bamberg, Fabian, et al., 2022. Framework and Baseline examination of the German national cohort (NAKO). Eur. J. Epidemiol. 37 (10), 1107–1124. https://doi.org/10.1007/s10654-022-00890-5.
Qin, Xiaochun, Li, Yanhua, Lin, Ma, Zhang, Yuping, Ni, Anchen, Wangari, Vicky Wangechi, 2024. The characteristics of noise propagation and distribution on the ultra-wide cross section of highways: a case study in Guangdong Province. Environ. Impact Assess. Rev. 104 (January), 107323. https://doi.org/10.1016/j.eiar.2023.107323.
Quintero, G., Balastegui, A., Romeu, J., 2018. Annual traffic noise levels estimation based on temporal stratification. J. Environ. Manag. 206 (January), 1–9. https://doi.org/10.1016/j.jenvman.2017.10.008.
R Core Team, 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Radicchi, Antonella, Dietrich, Henckel, Memmel, Martin, 2016. Citizens as smart, active sensors for a quiet and just city. The case of the 'open source soundscapes' approach to identify, assess and plan 'everyday quiet areas' in cities. Noise Mapp. 5 (1), 1–20. https://doi.org/10.1515/noise-2018-0001.
Riedel, Natalie, Scheiner, Joachim, Müller, Grit, Köckler, Heike, 2014. Assessing the relationship between objective and subjective indicators of residential exposure to road traffic noise in the context of environmental justice. J. Environ. Plann. Manag. 57 (9), 1398–1421. https://doi.org/10.1080/09640568.2013.808610.
Riedel, Natalie, Köckler, Heike, Scheiner, Joachim, Berger, Klaus, 2015. Objective exposure to road traffic noise, noise annoyance and self-rated poor health – framing the relationship between noise and health as a matter of multiple stressors and resources in urban neighbourhoods. J. Environ. Plann. Manag. 58 (2), 336–356. https://doi.org/10.1080/09640568.2013.859129.
Riedel, Natalie, Köckler, Heike, Scheiner, Joachim, Van Kamp, Irene, Erbel, Raimund, Loerbroks, Adrian, Claßen, Thomas, Bolte, Gabriele, 2018. Home as a place of noise Control for the elderly? A cross-sectional study on potential mediating effects and associations between road traffic noise exposure, access to a quiet side, dwelling-related green and noise annoyance. Int. J. Environ. Res. Publ. Health 15 (5), 1036. https://doi.org/10.3390/ijerph15051036.
Rompel, Sarah, Schneider, Alexandra, Peters, Annette, Kraus, Ute, INGER Study Group, 2021. Sex/gender-differences in the health effects of environmental noise exposure on hypertension and ischemic heart disease—a systematic review. Int. J. Environ. Res. Publ. Health 18 (18), 9856. https://doi.org/10.3390/ijerph18189856.
Sapena, Marta, Kühnl, Marlene, Wurm, Michael, Patino, Jorge E., Duque, Juan C., Taubenböck, Hannes, 2022. Empiric recommendations for population disaggregation under different data scenarios. PLoS One 17 (9), e0274504. https://doi.org/10.1371/journal.pone.0274504.
Schubert, Melanie, Starke, Karla Romero, Gerlach, Julia, Reusche, Matthias, Kaboth, Pauline, Schmidt, Wolfram, Friedemann, Dieter, et al., 2023. Traffic-related high sleep disturbance in the LIFE-adult cohort study: a comparison to the WHO exposure-response-curves. Int. J. Environ. Res. Publ. Health 20 (6), 4903. https://doi.org/10.3390/ijerph20064903.
Shrestha, Rehana, Flacke, Johannes, Martinez, Javier, Maarseveen, Martin van, 2016. Environmental health related socio-spatial inequalities: identifying 'hotspots' of environmental burdens and social vulnerability. Int. J. Environ. Res. Publ. Health 13 (7), 691. https://doi.org/10.3390/ijerph13070691.
Singh, Daljeet, Nigam, S.P., Agrawal, V.P., Kumar, Maneek, 2016. Vehicular traffic noise prediction using soft computing approach. J. Environ. Manag. 183 (December), 59–66. https://doi.org/10.1016/j.jenvman.2016.08.053.
Skånberg, A., Öhrström, E., 2002. Adverse health effects in relation to urban residential soundscapes. J. Sound Vib. 250 (1), 151–155. https://doi.org/10.1006/jsvi.2001.3894.
Staab, Jeroen, Schady, Arthur, Weigand, Matthias, Lakes, Tobia, Taubenböck, Hannes, 2022. Predicting traffic noise using land-use regression—a scalable approach. J. Expo. Sci. Environ. Epidemiol. 32, 232–243. https://doi.org/10.1038/s41370-021-00355-z.
Staab, Jeroen, Stark, Thomas, Wurm, Michael, Wolf, Kathrin, Dallavalle, Marco, Schady, Arthur, Lakes, Tobia, Taubenböck, Hannes, 2023. Using CNNs on sentinel-2 data for road traffic noise modelling. In: 2023 Joint Urban Remote Sensing Event (JURSE), pp. 1–4. https://doi.org/10.1109/JURSE57346.2023.10144160.
Stansfeld, S.A., 2003. Noise pollution: non-auditory effects on health. Br. Med. Bull. 68 (1), 243–257. https://doi.org/10.1093/bmb/ldg033.
Steele, Campbell, 2001. A critical review of some traffic noise prediction models. Appl. Acoust. 62 (3), 271–287. https://doi.org/10.1016/S0003-682X(00)00030-X.
Stimac, Alan, 2005. Implementation of Directive 2002/49/EC in EU Candidate State: Experience in Croatian Noise Mapping Projects. Budapest. https://www.researchgate.net/profile/Alan-Stimac/publication/228479304_Implementation_of_Directive_200249EC_in_EU_Candidate_State_Experience_in_Croatian_noise_mapping_projects/links/57dbce7c08aeea195934f2c1/Implementation-of-Directive-2002-49-EC-in-EU-Candidate-State-Experience-in-Croatian-noise-mapping-projects.pdf.
Szczepańska, Agnieszka, Senetra, Adam, Wasilewicz-Pszczółkowska, Monika, 2020. The influence of traffic noise on apartment prices on the example of a European urban agglomeration. Sustainability 12 (3), 801. https://doi.org/10.3390/su12030801.
Taubenböck, H., Weigand, M., Esch, T., Staab, J., Wurm, M., Mast, J., Dech, S., 2019. A new ranking of the world's largest cities—do administrative units obscure morphological realities? Rem. Sens. Environ. 232 (October), 111353. https://doi.org/10.1016/j.rse.2019.111353.
Taubenböck, H., Droin, A., Standfuß, I., Dosch, F., Sander, N., Milbert, A., Eichfuss, S., Wurm, M., 2022. To Be, or not to Be 'urban'? A multi-modal method for the differentiated measurement of the degree of urbanization. Comput. Environ. Urban Syst. 95 (July), 101830. https://doi.org/10.1016/j.compenvurbsys.2022.101830.
The Lancet Regional Health – Europe, 2023. Noise pollution: more attention is needed. The Lancet Regional Health - Europe 24 (January), 100577. https://doi.org/10.1016/j.lanepe.2022.100577.
Tiwari, S.K., Kumaraswamidhas, L.A., Garg, N., 2023. Strategies and implications of noise pollution monitoring, modelling, and mitigation in urban cities. In: Aswal, Dinesh K., Yadav, Sanjay, Takatsuji, Toshiyuki, Rachakonda, Prem, Kumar, Harish (Eds.), Handbook of Metrology and Applications. Springer Nature, Singapore, pp. 1571–1593. https://doi.org/10.1007/978-981-99-2074-7_86.
Van Kempen, Elise, Casas, Maribel, Pershagen, Göran, Foraster, Maria, 2018. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary. Int. J. Environ. Res. Publ. Health 15 (2), 379. https://doi.org/10.3390/ijerph15020379.
Vidaña-Vila, Ester, Navarro, Joan, Borda-Fortuny, Cristina, Stowell, Dan, Ma Alsina-Pagès, Rosa, 2020. Low-cost distributed acoustic sensor network for real-time urban sound monitoring. Electronics 9 (12), 2119. https://doi.org/10.3390/electronics9122119.
Voss, Stephan, Schneider, Alexandra, Huth, Cornelia, Wolf, Kathrin, Markevych, Iana, Schwettmann, Lars, Rathmann, Wolfgang, Peters, Annette, Breitner, Susanne, 2021. Long-term exposure to air pollution, road traffic noise, residential greenness, and prevalent and incident metabolic syndrome: results from the population-based KORA F4/FF4 cohort in Augsburg, Germany. Environ. Int. 147 (February), 106364. https://doi.org/10.1016/j.envint.2020.106364.
Wang, Zeshen, Müller, Jean-Claude, 1998. Line generalization based on analysis of shape characteristics. Cartogr. Geogr. Inf. Syst. 25 (1), 3–15. https://doi.org/10.1559/152304098782441750.
Wang, Haibo, Cai, Ming, Yao, Yifan, 2017. A modified 3D algorithm for road traffic noise attenuation calculations in large urban areas. J. Environ. Manag. 196 (July), 614–626. https://doi.org/10.1016/j.jenvman.2017.03.039.
Weigand, Matthias, Wurm, Michael, Dech, Stefan, Taubenböck, Hannes, 2019. Remote sensing in environmental justice research—a review. ISPRS Int. J. GeoInf. 8 (1), 20. https://doi.org/10.3390/ijgi8010020.
WG-AEN, 2007. Good practice Guide for strategic noise mapping and the production of associated data on noise exposure. European Commission Working Group Assessment of Exposure to Noise, second ed. http://www.lfu.bayern.de/laerm/eg_umgebungslaermrichtlinie/doc/good_practice_guide_2007.pdf.
Wolf, Kathrin, Schikowski, T., Dallavalle, M., Niedermayer, Fiona, Bolte, Gabriele, Lakes, Tobia, Moebus, S., Schneider, A., Peters, A., Hoffmann, B., 2023. Environmental exposure assessment in the German national cohort (NAKO). Eur. J. Publ. Health 33 (October). https://doi.org/10.1093/eurpub/ckad160.501.
Wolf, Kathrin, Dallavalle, Marco, Niedermayer, Fiona, Bolte, Gabriele, Lakes, Tobia, Schikowski, Tamara, Halina Greiser, Karin, et al., 2025. Environmental exposure assessment in the German national cohort (NAKO). Environ. Res. 273 (May), 121259. https://doi.org/10.1016/j.envres.2025.121259.
World Health Organization, 2011. In: Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe. Copenhagen: World Health Organization, Regional Office for Europe. https://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf.
Wurm, Michael, d'Angelo, Pablo, Reinartz, Peter, Taubenböck, Hannes, 2014. Investigating the applicability of Cartosat-1 DEMs and topographic maps to localize large-area urban mass concentrations. IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 7 (10), 4138–4152. https://doi.org/10.1109/JSTARS.2014.2346655.
Xie, Dan, Liu, Yi, Chen, Jining, 2011. Mapping urban environmental noise: a land use regression method. Environ. Sci. Technol. 45 (17), 7358–7364. https://doi.org/10.1021/es200785x.

Xie, Hui, Kang, Jian, Roger, Tompsett, 2011. The impacts of environmental noise on the academic achievements of secondary school students in Greater London. Appl. Acoust. 72 (8), 551–555. https://doi.org/10.1016/j.apacoust.2010.10.013.

Yoo, Jisu, Kim, Min-jong, Choi, Tae Muk, Seo, Il Chang, 2024. Development of web-based software for environmental impact assessment focusing on road traffic noise. J. Environ. Manag. 360 (June), 120926. https://doi.org/10.1016/j.jenvman.2024.120926.

Zapata, Oscar, Honey-Rosés, Jordi, 2022. The behavioral response to increased pedestrian and staying activity in public space: a field experiment. Environ. Behav. 54 (1), 36–57. https://doi.org/10.1177/0013916520953147.

Zhuang, Sida, Wolf, Kathrin, Schmitz, Tillman, Roth, Alexandra, Sun, Yukai, Savaskan, Nicolai, Lakes, Tobia, 2024. Neighborhood-level inequalities and influencing factors of COVID-19 incidence in Berlin based on Bayesian spatial modelling. Sustain. Cities Soc. 104 (May), 105301. https://doi.org/10.1016/j.scs.2024.105301.

Zijlema, Wilma, Cai, Yutong, Doiron, Dany, Mbatchou, Stéphane, Fortier, Isabel, Gulliver, John, de Hoogh, Kees, et al., 2016. Road traffic noise, blood pressure and heart rate: pooled analyses of harmonized data from 88,336 participants. Environ. Res. 151 (November), 804–813. https://doi.org/10.1016/j.envres.2016.09.014.