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Evaluation of the benefits of green space on noise-related effects: a health impact assessment on annoyance

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Summary

Quiet or tranquil areas are widely recognised for their positive impact on individual and community well-being, providing relief from urban noise and stress. These areas offer more than just an absence of noise—they include pleasant environmental sounds, such as those from water, wind, and wildlife, along with visual elements like green spaces and open landscapes.

This report assesses the health benefits of having quiet areas within European agglomerations by quantifying potential reductions in noise annoyance from road traffic and railway noise through increased green spaces exposure, as a surrogate for health effects from quiet areas. Noise exposure data were sourced from the latest Environmental Noise Directive (END) mapping of agglomerations with over 100,000 adult inhabitants. Agglomeration-level green space exposure was taken from an existing health impact assessment of 1,000 European cities, using the Normalized Difference Vegetation Index (NDVI) to determine the mean intensity of green within agglomerations. NDVI is a satellite-based measure of land surface reflectance or "greenness" that captures street trees, green corridors and parks, and general vegetation within public and private spaces. Baseline annoyance levels were assessed using exposure-response functions (ERFs) from the 2018 WHO Environmental Noise Guidelines, with the modifying effect of green spaces on reducing annoyance taken from a population-based survey in Switzerland. Two scenarios exploring how increased green space exposure could reduce noise annoyance among adults were considered: (1) achieving WHO recommendations for universal access to green spaces (i.e. at least 0.5 hectares within a 300 m or a 5-minute walk from home); and (2) an incremental increase in green spaces by 10%. Disability Adjusted Life Years (DALYs) were calculated using a disability weight of 0.011 per highly annoyed person, according to the new empirical evidence from the WHO.

In the first scenario, it was estimated that approximately 38% of the adult population live in areas that do not meet the access to green spaces target recommended by the WHO. Achieving the targets for all agglomerations could potentially reduce the number of people highly annoyed by road traffic noise by 104,486, which is a 1.1% decrease from the current annoyance levels as estimated using 2022 END data. This improvement would result in 86 fewer highly annoyed individuals per 100,000 adult inhabitants and prevent 1,149 DALYs. For railway noise annoyance, this approach could reduce the number of highly annoyed individuals by 10,210, representing a 0.7% reduction, with 9 fewer highly annoyed individuals per 100,000 adult inhabitants and preventing 112 DALYs.

In the second scenario, increasing green space by 10% across all agglomerations could reduce noise annoyance by 882,673 for road traffic noise, which is a 9.6% reduction from the current annoyance levels. This would equate to 724 fewer highly annoyed individuals per 100,000 adult inhabitants and prevent 9,709 DALYs. For railway noise, the 10% increase in green space could decrease the number of highly annoyed individuals by 92,940 or 6.8%, resulting in 80 fewer highly annoyed individuals per 100,000 adult inhabitants and preventing 1,022 DALYs.

The results of this case study underscore the significant health benefits of enhancing green-quiet areas in urban settings to mitigate noise pollution. While green spaces are crucial to fostering tranquillity, other factors such as pleasant sounds and visual aesthetics also contribute to the overall concept of tranquillity. The actual health benefits of tranquillity is expected to comprise substantially more than reduction in noise annoyance from increased green space, but this remains unquantifiable to date. Integrating these findings into urban planning and public health policies is essential for developing healthier, more liveable, and resilient cities.

1 Introduction

Urban environments, while central to modern living, often present significant public health challenges, particularly through environmental issues such as noise pollution. As Europe continues to urbanize, mitigating noise pollution has become essential for safeguarding residents' health and well-being.

Quiet, green or tranquil areas within urban environments are recognized for their potential to mitigate the adverse effects of noise pollution. Tranquillity is not merely the absence of noise; it encompasses a multidimensional experience that includes pleasant sounds such as those from water, wind, and wildlife. Natural elements, especially green spaces further enhance the sense of tranquillity. Research has established that access to green spaces can reduce perceived noise levels and fosters physical and mental health benefits. Quiet areas offer significant relief from the pervasive noise and stress of urban living, positively contributing to both individuals' and communities' well-being.

The European Environment Agency (EEA), alongside the European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM), has underscored the importance of understanding both the extent of noise exposure and the potential benefits of quiet areas. Efforts to designate and preserve quiet areas in Europe trace back to the publication of "Quiet areas in Europe – The environment unaffected by noise" in 2016 and the development of the Quietness Suitability Index (QSI) (EEA, 2016). The QSI integrates anthropogenic noise and land cover data to identify potential quiet areas at the European level. This methodology was also applied to Natura 2000 sites, which are areas of high biodiversity value protected under the Habitats Directive and cover more than 18% of European land. It was found that almost 27% of these protected sites are havens of quiet. From 2019 to 2021, the investigation into quiet areas expanded to assess the availability and accessibility of potential quiet areas with green land cover within urban spaces. Key insights from this research were published in the "Environmental Noise in Europe – 2020" report and the ETC/HE report titled "Potential Quiet Areas in END Agglomerations," contributing to the Environmental Health Atlas (EEA, 2019, 2022).

Despite these efforts, estimating the potential health benefits of quiet areas remains challenging due to the lack of established methods to measure quietness exposure and the scarcity of epidemiological research. The QSI, while promising, has not yet been utilized in epidemiological studies to investigate the health effects of quiet areas. The main issue being that the QSI by design uses the absence of environmental noise as a key criteria, a situation rarely met within areas inhabited by humans. Previous research has explored various indirect measures—referred to as surrogates—to estimate the benefits of quiet areas. These surrogates include visual quality, land use type, accessibility, and subjective perception, which serve as proxies to infer or approximate the effects of quiet areas.

This report aims to address these gaps by conducting a literature review and an EU-level health impact assessment to identify and evaluate these surrogates for characterizing quiet areas and assessing their associated health effects.

2 Material and methods

2.1 Narrative review of surrogate measures for quiet areas and their health benefits

2.1.1 Objective and methodological approach

The objective of this narrative review is to identify and evaluate surrogate measures for characterizing quiet areas and their associated health benefits. A literature search was conducted using PubMed with keywords such as "quiet areas," "tranquil areas," "definitions" and related terms, limited to articles published in English up to December 2023. The review prioritized epidemiological data linking health outcomes with various exposure surrogates. Findings were synthesized narratively, summarizing key characteristics, methodologies, and health outcomes related to quiet areas. Studies were compiled to illustrate the practical applications of each surrogate measure and their relevance to health outcomes.

2.1.2 Data extraction and quality assessment

The data extraction process was performed by one researcher (XJ) and subsequently reviewed by two other researchers (DV, MR). The quality of evidence was assessed based on study design, sample size, and analytical robustness.

2.1.3 Results from narrative review

Criteria for quietness

The definition of quiet areas lacks a precise consensus, yet there is a general agreement that these areas are characterized by an absence or low dominance of anthropogenic noise. In contrast to undesirable man-made noise, the presence of natural sounds — such as rustling leaves, flowing water, birdsong, or the soothing sounds of an urban fountain — significantly contribute to the perception of tranquillity (Ratcliffe, 2021; Aletta et al., 2018).

Green and blue spaces further enhance the notion of tranquillity. Green spaces generally include natural vegetation such as grass, plants, or trees, and may be built environmental features such as urban parks along with less regulated areas such as nature reserves. These environments not only act as natural barriers against environmental noise but also significantly enhance aesthetic appeal. Similarly, blue spaces (rivers, lakes, sea) can contribute to visual aesthetic and tranquillity, providing corresponding health benefits as demonstrated in recent systematic reviews (Gascon et al., 2017; White et al., 2020, 2021). Two common objective metrics are used to quantify green space in epidemiological studies:

1. Land use data: These data categorizes green spaces based on physical, mapped areas such as parks, gardens, and designated natural areas. Land use maps help identify green spaces with specific boundaries and purposes, although their coverage can be limited. Metrics such as the percentage of green land use within specified radii (i.e. circular buffer distances) around a residential location are often used.
2. Normalized Difference Vegetation Index (NDVI): NDVI is a satellite-based measure of land surface reflectance or “greenness” that captures all vegetation e.g. from ground cover, trees, green corridors and parks, within both public and private spaces. It is measured on a scale between -1 and 1, where values < 0.1 represents barren areas, sand or snow; 0.2–0.3 represent shrub and grassland; and values > 0.3 indicate increasing intensity of green (Weier and Herring, 2000).

In this report, “green space” is used interchangeably to refer to both physical green areas (as identified from land-use maps) and greenness (measured through NDVI). Subjective measures are also commonly used to assess the presence and quality of green spaces. These include perceived green from home, where participants are asked to rate the amount of visible green and perceived neighbourhood greenery based on a verbal scale. Other measures include courtyard quality, which assesses the presence of greenery and natural elements in shared outdoor spaces.

Accessibility of quiet areas is another important criterion for defining quiet areas. Assessing accessibility involves considering factors such as proximity, ease of travel, and the availability of roads and pathways to quiet areas. Homes with a quiet façade — having at least one window facing a yard, blue space, or green space — may also be considered as an indicator of accessibility to quiet areas.

Health effects of quiet (and natural) areas

Many experimental and survey studies consistently showed that exposure to natural sounds improves cognitive performance and aids in stress recovery in humans (Krzywicka and Byrka, 2017; Zhang et al., 2017). A systematic review and meta-analysis provided evidence supporting the positive influence of natural sounds on decreased stress and annoyance, with a mean effect of −0.6 (95 % Confidence Interval −0.97, −0.23), and improved overall health and positive affective outcomes (mean effect size 1.63, 95 % CI 0.09, 3.16) (Buxton et al., 2021). However, the studies identified in this systematic review and from current literature are dominated by small-scale experimental studies focusing on short-term effects of natural sounds. These studies are challenging to use in applications aimed at evaluating long-term health outcomes at the population level.

Extensive systematic reviews and meta-analyses provided compelling evidence of the positive health impact of green spaces, demonstrating inverse associations with type II diabetes, cardiovascular diseases, mental health issues, adverse birth outcomes, cancer, and all-cause mortality (Jimenez et al., 2021; Masdor et al., 2023; Rojas-Rueda et al., 2019; Twohig-Bennett and Jones, 2018). For example, a meta-analysis of 103 observational and 40 interventional studies published before January 2017 found that the risk of type II diabetes decreased with an odds ratio (OR) of 0.72 (95 % CI 0.61, 0.85) and cardiovascular disease mortality with an OR of 0.84 (95 % CI 0.76, 0.93) in the highest green spaces exposure group compared to lowest exposure group (Twohig-Bennett and Jones, 2018). The same meta-analysis reported a reduced risk for preterm birth (OR = 0.87, 95 % CI 0.80, 0.94) and a decreased risk for small size for gestational age (OR = 0.81, 95 % CI 0.76, 0.86). A systematic review including 45 studies published from January 2000 to November 2020 found a consistent association between exposure to greenness and emotional and behavioural well-being in children (Davis et al., 2021). Another systematic review and meta-analysis of cohort studies published before August 2019 found a pooled all-cause mortality risk reduction of 4% (95 % CI 3%, 6%) per a 0.1 NDVI increment within a 500 m buffer around a participant's residence (Rojas-Rueda et al., 2019).

Health benefits associated with blue spaces have also been documented. A systematic review by Gascon et al., (2017) found positive correlations between exposure to outdoor blue spaces and improvements in mental health, well-being, and physical activity, though associations with general health, obesity, and cardiovascular disease were less frequently studied.

Studies also suggest that the accessibility of quiet, green, and blue areas is crucial for enhancing overall well-being (Shepherd et al., 2013). In a study of 2,612 residents from Malmö, Sweden, those living in homes or apartments with a quiet façade—defined as having at least one window facing a yard, water, or green space—had a significantly reduced risk of noise annoyance (OR = 0.47, 95% CI 0.38, 0.59) and concentration problems (OR = 0.76, 95% CI 0.61, 0.95) (Bodin et al., 2015). Additionally, having a bedroom window facing a quiet environment was associated with a decreased risk of poor sleep quality (OR = 0.80, 95% CI 0.64, 1.00).

Potential pathways for the beneficial effects of green spaces include increased motivation for physical activity in green spaces, reduced heat in summer, the relaxing effect of visible green, and reduced pollution including noise. Similarly, promotion of physical activity is considered a potential pathway for the beneficial effect of accessibility of quiet areas, as positive associations between physical activity and various urban environmental attributes, including the proximity of parks, were observed (Sallis et al., 2016, 2020).

Multidimensional nature of quietness

Understanding the health benefits of quiet areas requires examining the interplay between various defining criteria. Few studies have explored these dimensions together. For instance, some research has focused on the impact of green spaces on noise annoyance. A study in Plovdiv, Bulgaria, found that objective green space metrics, such as the NDVI and tree cover density, were associated with reduced noise annoyance, particularly when combined with perceived greenery and lower daytime noise levels (Dzhambov et al., 2018b). Similarly, research in Switzerland revealed that increased residential green, measured separately by NDVI and land-use classifications, correlated with lower annoyance from road traffic and railway noise. However, an unexpected increase in annoyance from aircraft noise was also observed (Schäffer et al., 2020).

2.1.4 Conclusions from narrative review

The narrative review highlighted the importance of adopting a holistic approach to assess quiet areas, recognizing the multidimensional nature of quietness. Key factors such as noise levels, natural sounds, visual appeal, and accessibility should be considered collectively to evaluate their potential health benefits.

While the health benefits of green spaces are well-established, research integrating the concept of tranquillity (or using noise levels as a proxy for quietness) remains limited. The narrative review identified a few studies addressing the modifying effects of green spaces on noise annoyance, whereas such research was scarce for other health outcomes.

In the absence of more comprehensive data, the subsequent health impact assessment employed a simplified approach, using green spaces as a surrogate for quiet areas and annoyance as the key health outcome. While this method has its limitations, the available evidence supports the notion that green spaces reduce noise annoyance and can thus improve public health. Future research should aim to develop more direct methods for assessing quietness and its broader health effects, ideally moving beyond noise annoyance to include other outcomes.

2.2 Quantitative health impact assessment

2.2.1 Overview

The health impact assessment aimed to estimate the effect of increased availability of green spaces on reducing the number of people highly annoyed by road traffic and railway noise, focusing on residents aged 18 years and older in agglomerations with more than 100,000 inhabitants reporting to the Environmental Noise Directive (END) (EC, 2002/49). This assessment utilized a comparative approach, evaluating the impact of two counterfactual scenarios:

- Counterfactual Scenario 1: Adhering to the WHO recommendation for universal residential access to green spaces (i.e., at least 0.5 hectares within 300 m or a 5-minute walk from home) (WHO, 2016), which is the only internationally recognized guideline.
- Counterfactual Scenario 2: An incremental increase in green spaces, examining the potential benefits of gradual improvements in green spaces coverage.

The potential reduction in high annoyance was calculated based on the percentage of highly annoyed residents (%HA) and the population size for each agglomeration. Exposure-response functions (ERFs) between the %HA and noise exposure levels (L_{den}, day-evening-night-level) from the review for the 2018 WHO Environmental Noise Guidelines were used to calculate the %HA for each agglomeration. The modifying effect of green spaces on these ERFs, determined through a literature review, was then applied to estimate the potential reduction in noise annoyance burden due to increased green spaces. Results were aggregated by agglomeration to estimate the benefits per 100,000 inhabitants, and the potential reduction in disability-adjusted life years (DALYs) was also calculated.

2.2.2 Deriving exposure-response function for health impact assessment

Literature search

To identify relevant literature that quantified the modifying effect of green spaces on noise annoyance, a literature review was conducted using PubMed, employing key terms detailed in Annex 1. The search aimed to identify reviews, ideally systematic reviews. In the absence of reviews with meta-analyses, primary studies referenced within the reviews were considered for further evaluation. The search was supplemented with a manual search using Google Scholar.

Studies needed to be observational, conducted in urban residential settings, and have clear, measurable definitions of both green spaces and noise metrics. The focus was on transportation noise, with the additional search term for environmental noise. Studies not directly addressing the relationship between green spaces and noise annoyance were excluded, as were studies on neighbor and occupational noise.

The data extraction process was performed by one researcher (XJ) and subsequently reviewed by another researcher (DV). The quality of evidence was assessed based on study design, sample size, and analytical robustness.

Key reviews identified

A total of five reviews were identified, including one systematic review (Peris and Fenech, 2020) found through the PubMed search and four additional reviews identified through reference checking and the manual search (Hasegawa and Lau, 2021; Li and Lau, 2020; Van Renterghem, 2019; Dzhambov and Dimitrova, 2014) (Table 2.1).

These reviews consistently showed that green spaces reduce noise annoyance. However, none of the reviews offered meta-analyses, and the primary studies included in the reviews ranged from very small samples to larger datasets. While this limits the generalizability of some findings, the overall body of evidence indicates that both visual and physical proximity to greenery can help mitigate the negative effects of noise pollution.

Table 2.1 Overview of identified reviews

Author(s)	Type of review	Search period	Number of relevant studies/total studies included ([a])	Main findings
Hasegawa and Lau (2021)	Systematic review	1 Jan 1976 – 1 May 2020	13/14	Greenery is the most important visual variable for moderating noise annoyance. Visual and audiovisual factors interact to influence noise perception and related responses.
Peris and Fenech (2020)	Systematic review	2000 – 2017	6/10	Noise exposure affects health through various pathways, including lifestyle and environmental factors. Greenness and access to quiet areas reduce negative responses to noise.
Li and Lau (2020)	Systematic review	1 Jan 1976 – 1 April 2019	2/2	Audio-visual interactions are crucial for soundscape assessment and noise control, providing guidelines for future research and experiment design.
Van Renterghem (2019)	Thematic review	Not specified	5/6	Visible vegetation mitigates noise annoyance through restorative properties and stress relief.
Dzhambov and Dimitrova (2014)	Systematic review	Until 4 June 2013	2/2	There is moderate evidence that vegetation reduces negative noise perception, serving as a psychological buffer against noise pollution.

([a]) The number of relevant studies identified for green spaces out of the total number of studies reviewed for noise annoyance. Some reviews examined multiple environmental factors, such as blue spaces, type of housing, and neighbourhood layout, but only studies focusing on green spaces were included in this evaluation.

Key findings from primary studies

Thirteen observational studies were identified across the reviews, employing cross-sectional designs and focusing on residential areas (Table 2.2). These studies had samples sizes ranging from 32 to 5,592 participants. Data collection was primarily through mailed surveys, with some studies utilizing field-survey questionnaires, focusing on the impacts of green spaces on noise annoyance. Both objective measures (e.g., NDVI, land use or tree cover density) and subjective measures (e.g., perceived availability of green spaces) were used to assess green exposure. The noise annoyance scales used were primarily international standardized 5-point verbal or 11-point numerical scales.

Most studies found that higher levels of green spaces were associated with lower noise annoyance. However, one study found no effect (Morihara et al., 2011), and another indicated that green spaces, evaluated via several different metrics, increased annoyance from aircraft noise while reducing it from road traffic and railway noise (Schäffer et al., 2020).

Table 2.2 Characteristics of relevant primary studies

Author(s)	Study location	Population (Response rate)	Green exposure	Noise source	Annoyance measurement	Main findings	Suitability for HIA
Gidlöf-Gunnarsson (2007)	Stockholm and Göteborg, Sweden	N = 500, 18-75 years, 59%	Access to green near dwelling (3-pt verbal scale)	Road traffic	11-pt numerical scale	The availability of nearby green areas and having access to a quiet side both contribute to a reduction in long-term noise annoyance. Improved access to green spaces significantly lowers residents' perception of annoyance from road traffic noise at home.	No, subjective green metric used
Gidlöf-Gunnarsson and Öhrström (2010)	Stockholm and Gothenburg, Sweden	N = 385, 18-75 years, 59%	Courtyard quality (low/high)	Road traffic	5-pt verbal scale (ISO)	Access to high-quality quiet courtyards was linked to reduced overall noise annoyance for individuals in both low and high noise exposure groups.	No, subjective green metric used
Li et al. (2010)	Hong Kong SAR, China	N = 688, 70%	Perceived greenery at home (3-pt verbal scale); Location × Greenery—view type (7-pt verbal scale)	Road traffic	5-pt verbal and 11-pt numerical scale (ISO)	Views of green spaces from high-rise buildings reduces noise annoyance more effectively than having limited greenery. This impact varies depending on the green settings.	No, subjective green metric used, highly selected population from specific estates of high-rise buildings

Author(s)	Study location	Population (Response rate)	Green exposure	Noise source	Annoyance measurement	Main findings	Suitability for HIA
Bodin et al. (2015)	Malmö, Sweden	N = 2612, 18-79 years, 54%	Dwelling/bedroom windows facing green spaces (yes/no)	Road traffic and railway	5-pt verbal scale (ISO)	Having a window facing green spaces was linked to a lower risk of noise annoyance.	No, subjective green metric used
Dzhambov and Dimitrova (2015)	Plovdiv, Bulgaria	N = 513, 18-83 years	Distance to nearest green spaces (in meter); Perceived neighbourhood greenness (10-pt scale); Time spent in green spaces per week; Presence of a garden at home; Perceived benefits of nature (11 questions, 7-pt Likert scale)	Perceived noise at home	11-pt numerical scale	Living farther from green spaces directly increased noise annoyance, while the perception of greenery was only indirectly related.	No, subjective green metric (except distance) and subjective noise used
Morihara et al. (2011)	Hanoi and Ho Chi Minh City, Vietnam	N = 2974	Perceived greenery in residential area (unspecified)	Road traffic and aircraft	5-pt verbal & 11-pt numerical scale (ICBEN)	The presence of residential greenery does not significantly affect noise annoyance due to road traffic and aircraft noise.	No, subjective green metric used, non-European population

Author(s)	Study location	Population (Response rate)	Green exposure	Noise source	Annoyance measurement	Main findings	Suitability for HIA
Li et al. (2012)	Hong Kong SAR, China	N = 861	Perceived greenery at home (3-pt verbal scale)	Road traffic	11-pt numerical scale (ISO)	The presence of green views can mitigate responses of annoyance. Individual-specific characteristics influence the perception of annoyance.	No, subjective green metric used, in highly selected Asian population from specific estates of high-rise buildings
Leung et al. (2014)	Hong Kong SAR, China	N = 1496, all ages	Greenery view from home (5-pt verbal scale)	Road traffic	11-pt numerical scale (ISO)	Perceiving greenery from home has a moderating effect on noise annoyance.	No, subjective green metric used, highly selected Asian population from specific estates of high-rise buildings
Van Renterghem and Botteldooren (2016)	Ghent, Belgium	N = 105, >= 18 years	View of green from living room (5-pt verbal scale)	Road traffic	5-pt verbal scale (ISO)	Views of vegetation can strongly lower self-reported annoyance levels.	No, subjective green metric used

Author(s)	Study location	Population (Response rate)	Green exposure	Noise source	Annoyance measurement	Main findings	Suitability for HIA
Leung et al. (2017)	Hong Kong SAR, China	N = 2033, mean age 40.75	Greenery view from home (5-pt verbal scale)	Road traffic	11-pt numerical scale (ISO)	Greenery views from high-rise buildings may reduce noise annoyance, whereas views of noise barriers may increase it.	No, subjective green metric used, highly selected Asian population from specific estates of high-rise buildings
Dzhambov et al. (2018a)	Plovdiv, Bulgaria	N = 720, 18-35 years, students	Perceived green spaces (5 questions, 6-pt scale)	Community and traffic noise	5-pt verbal scale (ICBEN)	Increased surrounding green spaces was linked to reduced noise annoyance, both due to lower noise exposure and higher perceived greenery.	No, subjective green metric used
Mueller et al. (2020)	Edinburgh, UK; Utrecht, Netherlands; Athens and Thessaloniki, Greece	N = 131, participants with children under 3-yr	NDVI; Annual tree cover density; Surrounding % green land use within 50m and 100m buffers around residence	Indoor noise measurements (capturing both indoor and outdoor sources)	11-pt numerical scale (ISO)	Higher residential greenness and tree cover correlated with reduced levels of annoyance from road traffic noise.	No, small population of household with children

Author(s)	Study location	Population (Response rate)	Green exposure	Noise source	Annoyance measurement	Main findings	Suitability for HIA
Schäffer et al. (2020)	Switzerland	N = 5592, representative of the Swiss population, 19-75 years, 31%	Five main residential green metrics in 500 m buffer around residence: NDVI (mean); green land use (m^2/m^2_{buffer}) ([a]); natural land use (m^2/m^2_{buffer}) ([a]); visible green (%); landscape suitability for nearby recreation	Road traffic, railway, and aircraft	5-pt verbal and 11-pt numerical scale (ICBEN)	Increasing residential green reduced annoyance from road traffic and railway noise but increased annoyance from aircraft noise. NDVI and green land use are important indicators in general, whereas the visibility and accessibility and or quietness of green spaces are important indicators of road traffic noise annoyance in urban areas.	Yes

Abbreviations: ISO: International Organization for Standardization; ICBEN: International Commission on Biological Effects of Noise; HIA: Health Impact Assessment.

([a]) Green land use and natural land use are from land use mapping.

Selection of Schäffer et al. (2020) for deriving exposure-response function

A meta-analysis was infeasible due to a lack of comparable studies with objective measures of green space (Table 2.2). Among the 13 observational studies identified, Schäffer et al. (2020) provides the necessary information for the subsequent health impact assessment due to several key reasons:

- **Comprehensive data**: Schäffer et al. (2020) used an extensive, national representative dataset with multiple objective green metrics. The other studies provide mostly subjective green metrics, which are difficult to apply in a health impact assessment.
- **Relevance to EU urban contexts**: Although the Swiss context may not perfectly represent all European areas, it provides a relevant basis for understanding the impact of green spaces in urban Europe. This is particularly pertinent when compared to studies focusing on highly selected populations, such as residents of specific high-rise estates (Leung et al., 2017; Li et al., 2010; Leung et al., 2014; Li et al., 2012) or small populations with specific characteristics, such as households with children (Mueller et al., 2020) and university students (Dzhambov et al., 2018a), which are less representative and therefore less suitable for this health impact assessment.
- **Detailed exposure response functions (ERFs):** Schäffer et al. (2020) provided detailed ERFs that quantify the relationship between noise exposure, green metrics, and noise annoyance levels. These functions are essential input for assessing potential health benefits of reducing noise annoyance through green spaces.

Extraction of ΔL from Schäffer et al. (2020) for exposure-response function

Schäffer et al. (2020) used modelled ERFs to demonstrate how different levels of residential greenery affect noise annoyance. The ERFs were plotted for the 5th, 50th, and 95th percentiles of the green metrics, representing neighborhoods with minimal, average, and extensive green. The presence of green shifted the ERFs on the L_{den} scale without changes in their slope, which is interpreted as an equivalent sound pressure level change (ΔL).

According to Schäffer et al. (2020), ΔL varies by noise source and green metric, and NDVI was identified as the best-suited green metric for describing the effects of residential green on annoyance, showing a reduction in annoyance from road traffic and railway noise but a more difficult to understand increase in annoyance from aircraft noise. Compared to other green metrics, such as cadastral land use mapping for green areas, which only captures designated green areas (e.g. forest, parks, gardens), NDVI captures all vegetated surfaces, including smaller, scattered greenery such as individual trees, shrubs, and grass. This broader scope makes NDVI particularly valuable for assessing the overall influence of total green spaces on noise annoyance. In their study, similar to others, NDVI was quantified within a 500 m circular buffer around the residential address.

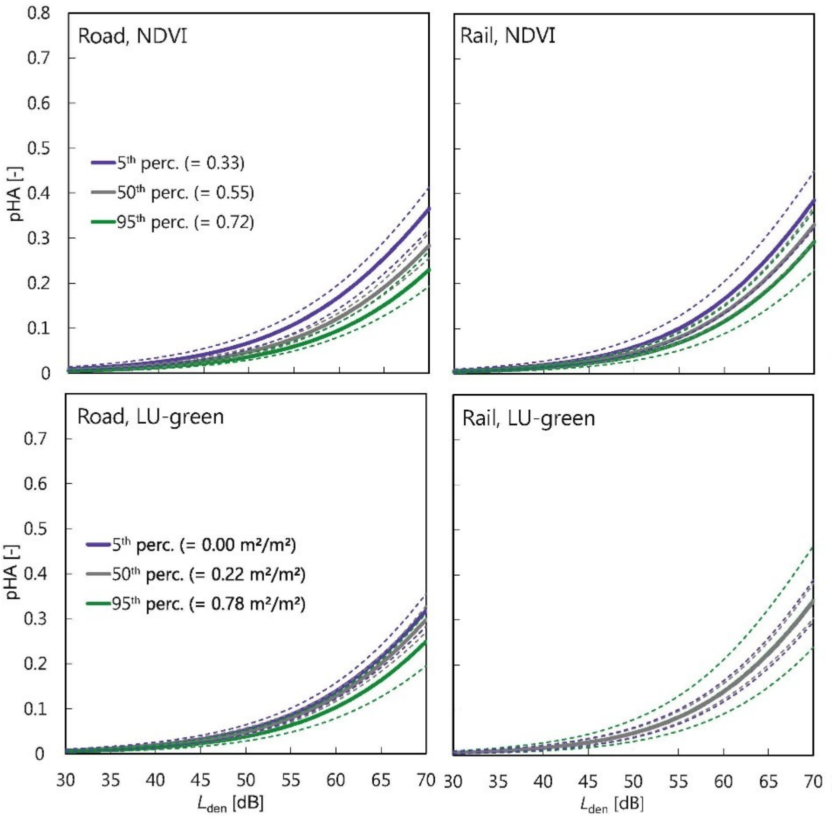
Table 2.3 and Figure 2.1 adapted from Schäffer et al. (2020) summarize the probability of high annoyance (pHA) as a function of the sound pressure level (L_{den}) at the 5th and 95th percentiles of NDVI for both road traffic and railway noise. In areas with higher residential green (95th percentile, NDVI = 0.72), the same probability of highly annoyed individuals is observed at noise levels (L_{den}) that are 6.3 dB higher for road traffic and 3.6 dB higher for railway noise, compared to areas with lower residential green (5th percentile, NDVI = 0.33). This indicates that increased residential green dampens the effect of noise, allowing higher noise levels before reaching the same probability of annoyance.

Table 2.3 Probability of high annoyance (pHA) as a function of the sound pressure level (L_{den}) at the 5th and 95th percentiles of NDVI

Noise source	NDVI percentile	Exposure-response function
Road	5th percentile	$pHA = 100 / [1 + \exp[-(-7.8087 + 0.1037 \times L_{den})]]$
	95th percentile	$pHA = 100 / [1 + \exp[-(-8.4661 + 0.1037 \times L_{den})]]$
Railway	5th percentile	$pHA = 100 / [1 + \exp[-(-8.5153 + 0.1150 \times L_{den})]]$
	95th percentile	$pHA = 100 / [1 + \exp[-(-8.9292 + 0.1150 \times L_{den})]]$

Source: Schäffer et al. (2020).

Figure 2.1 Exposure-response curves for the probability of high annoyance (pHA) as a function the sound pressure level (L_{den}) and residential green (top: NDVI, bottom: land use green) for road traffic (left) and railway noise (right), including 95 % CI



2.2.3 Exposure levels at baseline and counterfactual scenarios

Noise exposure data for road traffic and railway noise were extracted from the latest delivery reported under the END for the reference year 2022. The data include the number of people exposed per 1 dB noise band (L_{den}) for both noise sources, provided for each agglomeration.

Baseline exposure levels to green space

Exposure to green spaces was sourced from the ISGlobal ranking of cities - urban health study in 1,000 European cities, using the available NDVI means per city (Pereira Barboza et al., 2021). Their analysis was conducted for European cities and greater cities as defined in the Urban Audit 2018 dataset. Pereira Barboza et al. (2021) used 250 x 250 m NDVI data from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1), sourced from the US Geological Survey (Didan, 2015). The imagery was collected from April 1 to June 30, 2015 to capture peak greenness, after preprocessing to exclude cloudy, snowy, or icy pixels and water bodies. The resulting mean NDVI for each city served as baseline green levels in the current health impact assessment.

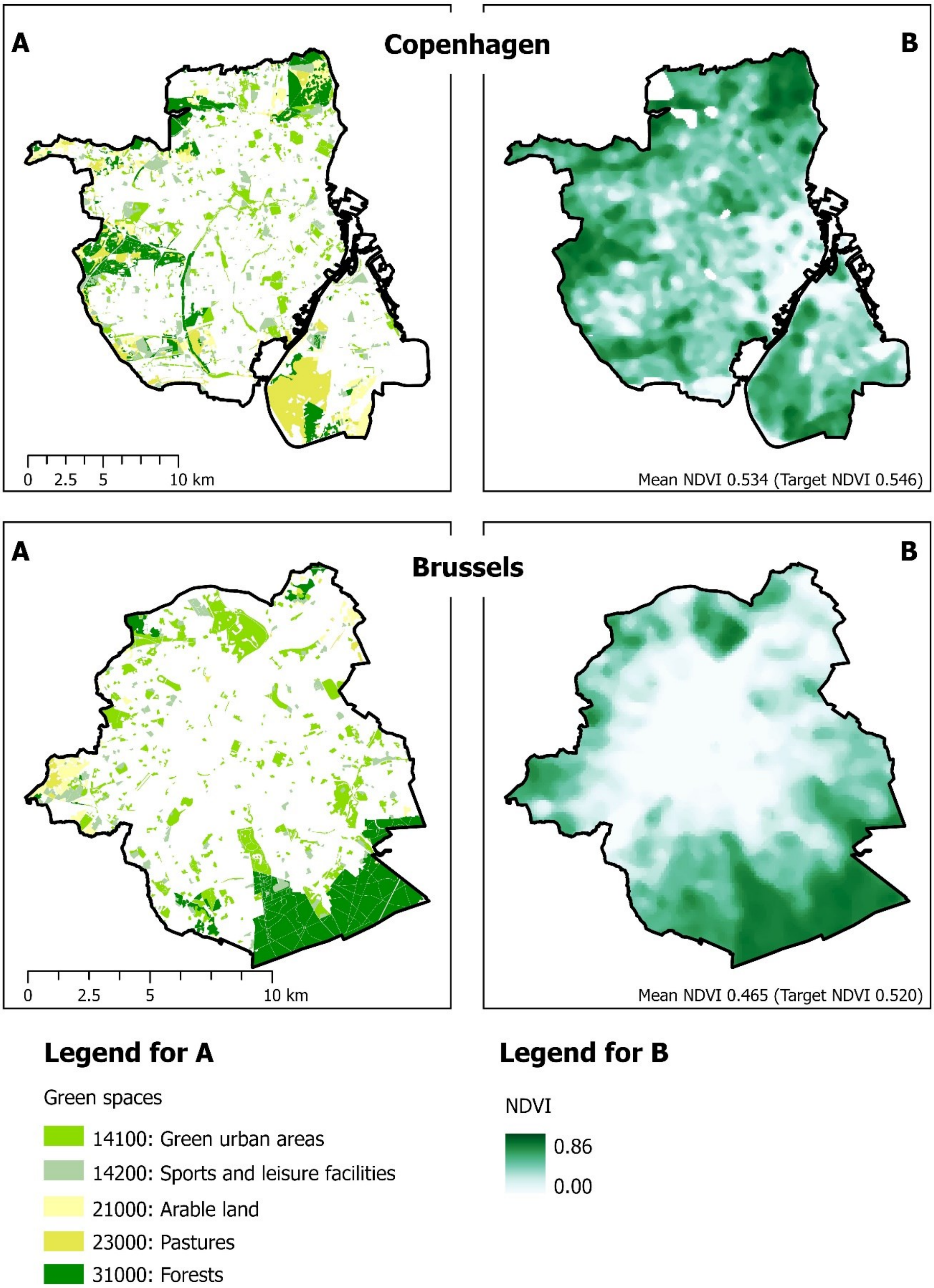
Counterfactual exposure levels to green space – Scenario 1

Previous studies of selected European cities have shown that universal access to green spaces, as recommended by the WHO (2016), is typically achieved when at least 25% of small census areas are green spaces (Mueller et al., 2017; Khomenko et al., 2020; Iungman et al., 2021). Further, a 300 m buffer was applied around each 250 x 250 m grid cell to align with WHO recommendation for universal access to green space of at least 0.5 hectares within a 5-minute walk from home (WHO, 2016). Based on this, Pereira Barboza et al. (2021) established a "target NDVI" for each city, i.e. how green a city needs to be to obtain universal access to green spaces, as an ideal target for urban planning. This target NDVI was calculated using a generalized additive model that relates the measured NDVI (which varies by city and latitude) to the actual proportion of green areas, derived from land-use maps, also within 250 x 250 m grid cells. Essentially, the model determines the NDVI value that corresponds to a 25% green area threshold, making it specific to each city's geographic and vegetative characteristics. It adjusts for non-linear relationships and local variations in vegetation density, ensuring that the target NDVI reflects the unique conditions of each urban area (Pereira Barboza et al., 2021).

In the current health impact assessment, this city-specific target NDVI serves as the counterfactual exposure level for Scenario 1. In this scenario, agglomerations that already meet the WHO recommendation for universal access to green space are excluded from the calculations, as no additional benefit is assumed.

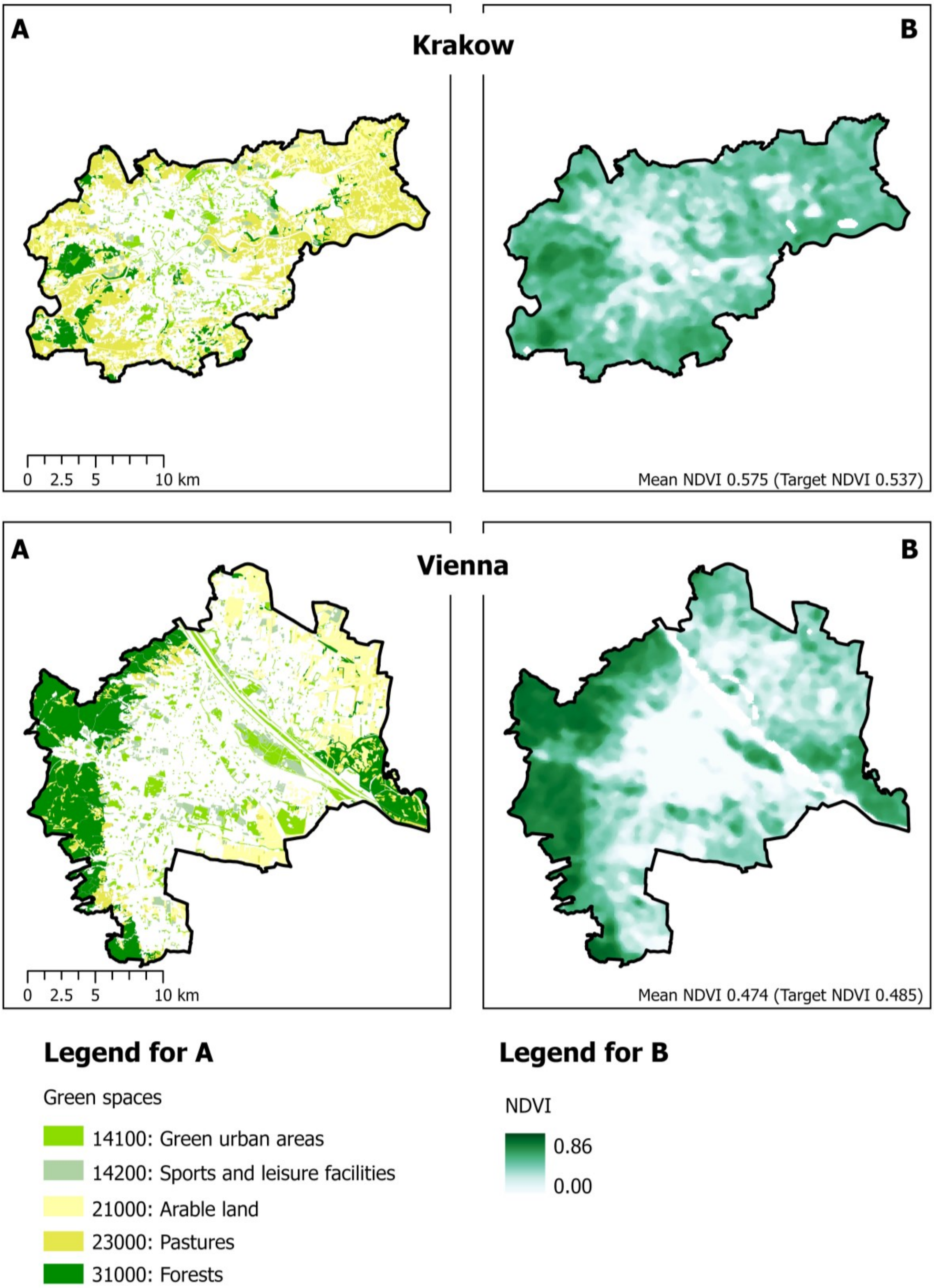
Map 2.1, Map 2.2, and Map 2.3 illustrate the current state of green space within selected agglomerations organised north to south: Copenhagen, Brussels, Krakow, Vienna, Turin, and Valencia. Panel A shows the distribution of actual green spaces within the agglomeration—parks, forests, and other green zones—based on Urban Atlas 2018 land use data. Panel B displays the NDVI distribution (from MODIS data), reflecting the overall greenness. The corresponding mean and target NDVI levels for each agglomeration are also indicated on the maps. These cities were selected to represent diverse geographic regions and types of agglomerations. Generally, mean and target NDVI values decrease from north to south, reflecting differences in vegetation density and climate. For example, Copenhagen, the northernmost agglomeration, has a mean NDVI of 0.534 and is close to meeting its target NDVI of 0.546, while Valencia, the southernmost, has a mean NDVI of 0.281 and has already met its target NDVI of 0.242.

Map 2.1 Green spaces and NDVI in Brussels, Belgium and Copenhagen, Denmark



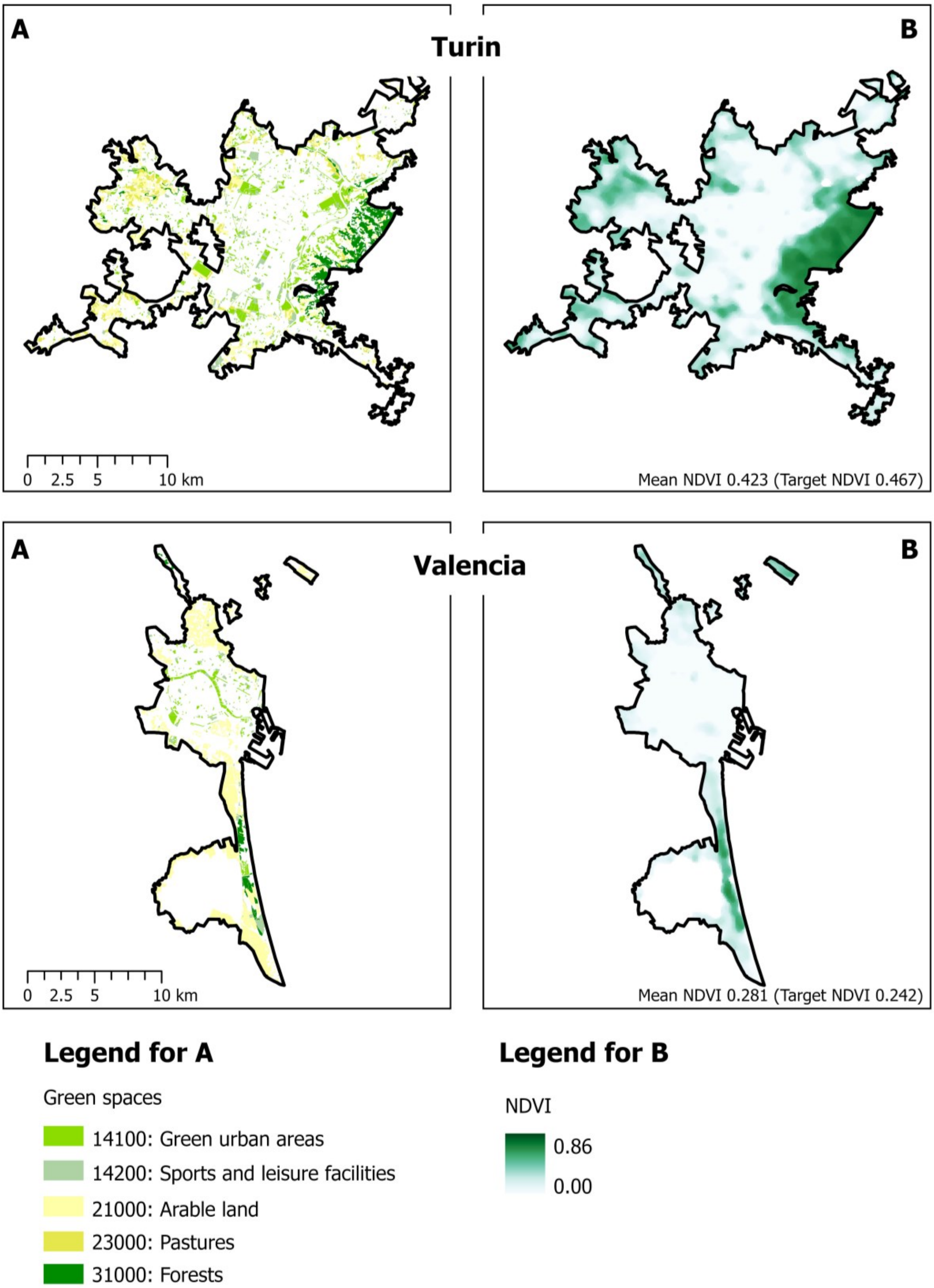
Data Source: Urban Atlas 2018 (green spaces) and MODIS (NDVI).

Map 2.2 Green spaces and NDVI in Krakow, Poland and Vienna, Austria



Data Source: Urban Atlas 2018 (green spaces) and MODIS (NDVI).

Map 2.3 Green spaces and NDVI in Turin, Italy and Valencia, Spain



Data Source: Urban Atlas 2018 (green spaces) and MODIS (NDVI).

Counterfactual exposure levels to green spaces – Scenario 2

The second counterfactual scenario considers a universal 10% increase in NDVI (i.e. increase by 0.1, given that NDVI is a unit-less measure scaled from -1 to 1, with green intensity being in the range 0 to 1) across all included agglomerations to explore the potential benefits of a consistent green space expansion across Europe. In this scenario, the 10% increase is applied even in the cities that already meet the WHO recommendation for universal access to green space.

Database integration

The Urban Audit 2018 dataset used as the basis for the 1,000 European cities study and END agglomerations were matched by name to incorporate (baseline and target) NDVI for the current health impact assessment. If a corresponding city (thus NDVI value) could not be found because the END agglomeration was part of a greater city, the NDVI value for the greater city was used; otherwise, those END agglomerations were excluded.

2.2.4 Evaluation of the impact

Two counterfactual scenarios were defined for each agglomeration in the health impact assessment:

- Scenario 1: Achieving target NDVI levels where current levels are below target.
- Scenario 2: A universal 10% increase in NDVI.

Exposure-response functions

For populations exposed to high levels of road traffic and railway noise (at least 55 dB L_{den}) (EEA, 2019), the annual number of adults experiencing high levels of annoyance was estimated using the ERFs from the review for the WHO Environmental Noise Guidelines (Guski et al., 2017). The functions used to estimate the baseline and counterfactual percentage of highly annoyed residents by L_{den} noise levels are shown in Table 2.4.

Table 2.4 Exposure-response functions for percentage of highly annoyed people (%HA) in relation to the annual 24-hour noise level (L_{den}) for road traffic and railway noise used in the health impact assessment

Road traffic noise	
Baseline scenario	$\%HA = (78.9270 - 3.1162 \times L_{den,\ road} + 0.0342 \times L_{den,\ road}^2)/100$
Scenario 1	$L_{den,\ road,\ s1} = L_{den,\ road} + [-6.3/(0.72 - 0.33)] \times (\text{target NDVI} - \text{mean NDVI})$
	$\%HA = (78.9270 - 3.1162 \times L_{den,\ road,\ s1} + 0.0342 \times L_{den,\ road,\ s1}^2)/100$
Scenario 2	$L_{den,\ road,\ s2} = L_{den,\ road} + [-6.3/(0.72 - 0.33)] \times (\text{mean NDVI} + 0.1)$
	$\%HA = (78.9270 - 3.1162 \times L_{den,\ road,\ s2} + 0.0342 \times L_{den,\ road,\ s2}^2)/100$
Railway noise	
Baseline scenario	$\%HA = (38.1596 - 2.05538 \times L_{den,\ railway} + 0.0285 \times L_{den,\ railway}^2)/100$
Scenario 1	$L_{den,\ railway,\ s1} = L_{den,\ railway} + [-3.6/(0.72 - 0.33)] \times (\text{target NDVI} - \text{mean NDVI})$
	$\%HA = (38.1596 - 2.05538 \times L_{den,\ railway,\ s1} + 0.0285 \times L_{den,\ railway,\ s1}^2)/100$
Scenario 2	$L_{den,\ railway,\ s2} = L_{den,\ railway} + [-3.6/(0.72 - 0.33)] \times (\text{mean NDVI} + 0.1)$
	$\%HA = (38.1596 - 2.05538 \times L_{den,\ railway,\ s2} + 0.0285 \times L_{den,\ railway,\ s2}^2)/100$

Source: Guski et al. (2017) and Schäffer et al. (2020).

For each agglomeration, baseline and counterfactual green exposure levels (NDVI) were sourced from Pereira Barboza et al. (2021) as explained in section 2.2.3. The difference in green exposure levels between the baseline and counterfactual scenarios was determined and linearly transformed into the equivalent sound pressure level change (ΔL, in dB) based on Schäffer et al. (2020). This yielded the equivalent noise exposure level in the counterfactual scenarios ($L_{den,\ s1}$ and $L_{den,\ s2}$). Subsequently, the percentage of the population highly annoyed by noise was calculated for both baseline and counterfactual scenarios. The potential reduction in the noise annoyance burden was then estimated.

Calculations were performed for the number of residents exposed to each noise band (per 1 dB), and the results were summed across all noise bands. A disability weight of 0.011 per highly annoyed person was applied to derive the potential reduction in DALYs (WHO, 2024). Results were aggregated at both the agglomeration and country levels to estimate the potential reduction in noise annoyance. All data analysis was conducted using R (Version 4.3.2).

3 Results

3.1 Results of the health impact assessment

The assessment included a total of 121,899,934 individuals aged 18 years or older (i.e. adults) from 417 agglomerations reporting to the END for road traffic noise. Among them, 9,218,282 individuals were highly annoyed by road traffic noise at baseline. For railway noise, the assessment included 116,308,118 adults from 396 agglomerations, with 1,364,867 individuals highly annoyed by railway noise at baseline.

Table 3.1 summarizes the estimated number of highly annoyed individuals due to road traffic and railway noise exposure at baseline, alongside the reduction in both the number and percentage of highly annoyed individuals in the counterfactual scenarios, as well as the corresponding reduction in DALYs. Figure 3.1 and Figure 3.2 present the estimated number and percentage reductions in highly annoyed adults across countries. Map 3.1 and Map 3.2 illustrate these reductions across agglomerations, with agglomeration size and percentage reduction displayed.

Table 3.1 Estimated reduction in highly annoyed adults by road traffic and railway noise due to green spaces exposure in the included agglomerations in 2022

Noise source	Baseline highly annoyed adults	Scenario	Reduction of highly annoyed adults	Percent reduction	Reduction in DALYs
Road traffic	9,218,282	Scenario 1	104,486	1.1%	1,149
		Scenario 2	882,673	9.6%	9,709
Railway	1,364,867	Scenario 1	10,210	0.7%	112
		Scenario 2	92,940	6.8%	1,022

Scenario 1 - Impact of achieving target NDVI levels

The majority of agglomerations have already met the WHO recommendation for universal access to green spaces, as determined by achieving or exceeding the city-specific target NDVI levels. For agglomerations affected by road traffic noise, 46,424,151 individuals (38.1% of the total adult population) from 100 different agglomerations live in areas where the current NDVI levels fall below the city-specific target. For railway noise, 45,569,735 individuals (39.1% of the total adult population) from 91 agglomerations live in areas with NDVI levels below the target. The overall health benefit in this scenario is thus attributed to improving NDVI levels in these populations.

For road traffic noise, increasing the availability of green areas to meet the target NDVI levels in the 100 agglomerations could potentially reduce the number of highly annoyed individuals at the European level by 104,486 annually, representing a 1.1% reduction (i.e., 86 fewer highly annoyed individuals per 100,000) (Table 3.1). This reduction corresponds to the prevention of 1,149 DALYs. France leads with the largest potential reduction in road noise annoyance if the green space target is met, accounting for a reduction of 57,513 highly annoyed individuals (55.0% of the total reduction). This is followed by the Netherlands (9,077 individuals, 8.7%), Germany (8,476 individuals, 8.1%), and Italy (6,212 individuals, 6.0%) (Figure 3.1). The agglomerations with the greatest potential reduction are Paris and Lyon (France); Turin (Italy); Amsterdam and The Hague (the Netherlands); Bucharest (Romania); Budapest (Hungary); Brussels (Belgium); Berlin (Germany); and Vienna (Austria) (Annex 2, Map 3.1).

For railway noise, meeting the target NDVI for the 91 agglomerations could reduce the number of highly annoyed individuals in Europe by 10,210 annually, representing a 0.7% reduction (i.e., 9 fewer highly annoyed individuals per 100,000) (Table 3.1). This would translate into the prevention of 112 DALYs. France also has the largest potential for reducing railway noise annoyance, accounting for a reduction of 5,056 individuals (49.5% of the total reduction), followed by Germany with 1,744 individuals (17.1%) (Figure 3.2). The agglomerations with the highest potential reduction are Paris, Aubergenville, and Lyon (France); Berlin and Munich (Germany); Vienna (Austria); Bucharest (Romania); Turin (Italy); Budapest (Hungary); and Antwerp (Belgium) (Annex 2, Map 3.2).

Scenario 2 - Impact of incremental NDVI increase

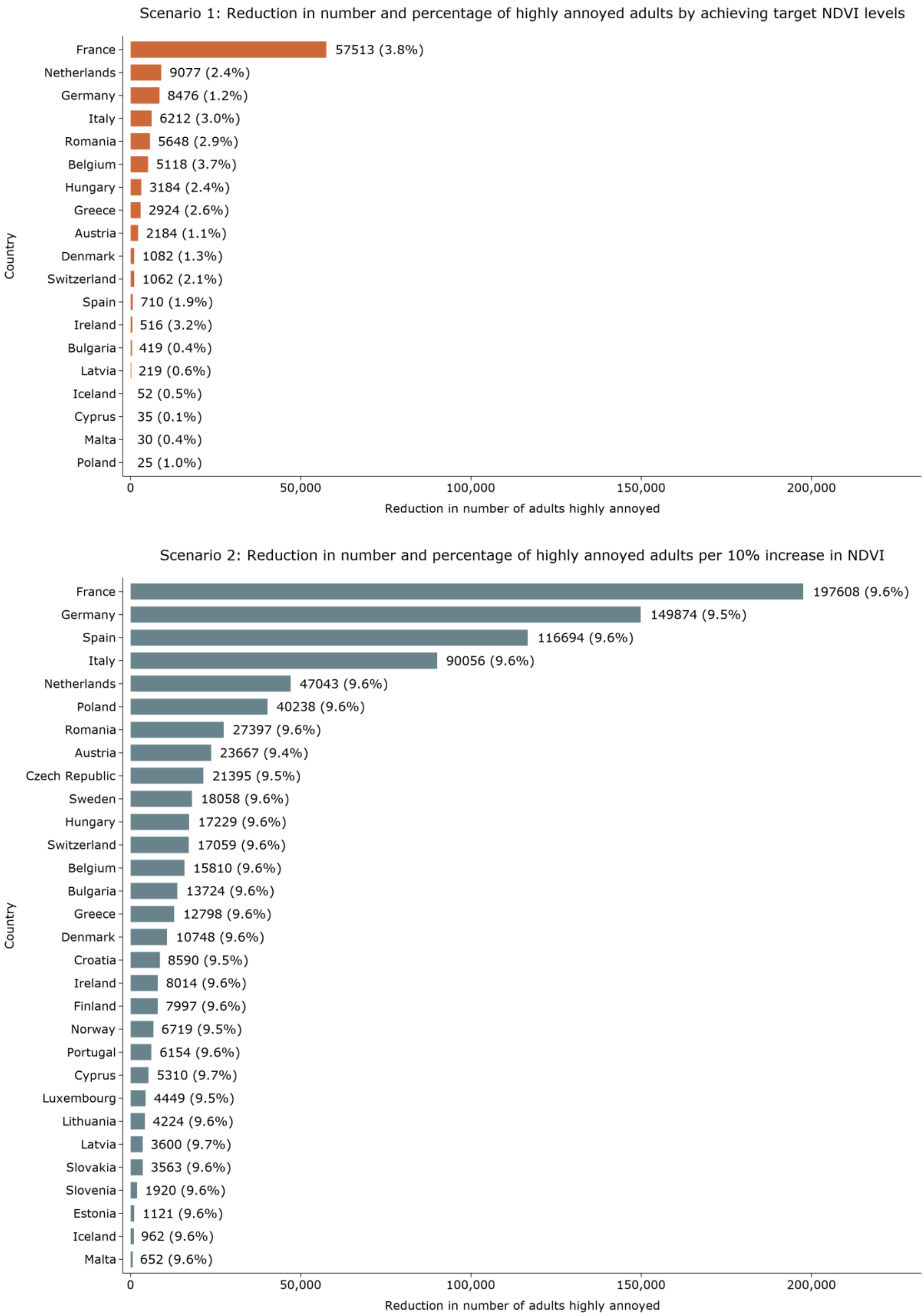
Greater benefit, in terms of reducing the number of individuals highly annoyed by transportation noise, is achieved when the availability of green spaces, as evaluated by NDVI, is universally increased across all agglomerations by 10% (Scenario 2 vs. Scenario 1, Map 3.1 and Map 3.2).

A 10% increase in the mean NDVI across all agglomerations could potentially reduce the number of highly annoyed individuals by 882,673 (9.6% reduction comparing to baseline) for road traffic noise (i.e., 724 fewer highly annoyed individuals per 100,000), preventing 9,709 DALYs (Table 3.1). For railway noise, this increase in NDVI could reduce the number of highly annoyed individuals by 92,940 (6.8%, 80 fewer highly annoyed individuals per 100,000), preventing 1,022 DALYs (Table 3.1Table 3.1).

For road traffic noise, France leads with the largest reduction in annoyance, accounting for a reduction of 197,608 highly annoyed individuals (22.4% of the total reduction). This is followed by Germany (149,874, 17.0%), Spain (116,694, 13.2%), and Italy (90,056, 10.2%) (Figure 3.1). The top 10 agglomerations with the highest potential reduction are Paris, Marseille, and Lyon (France); Madrid (Spain); Vienna (Austria); Berlin (Germany); Milan-Monza and Rome (Italy); Prague (Czech Republic); and Budapest (Hungary) (Annex 2).

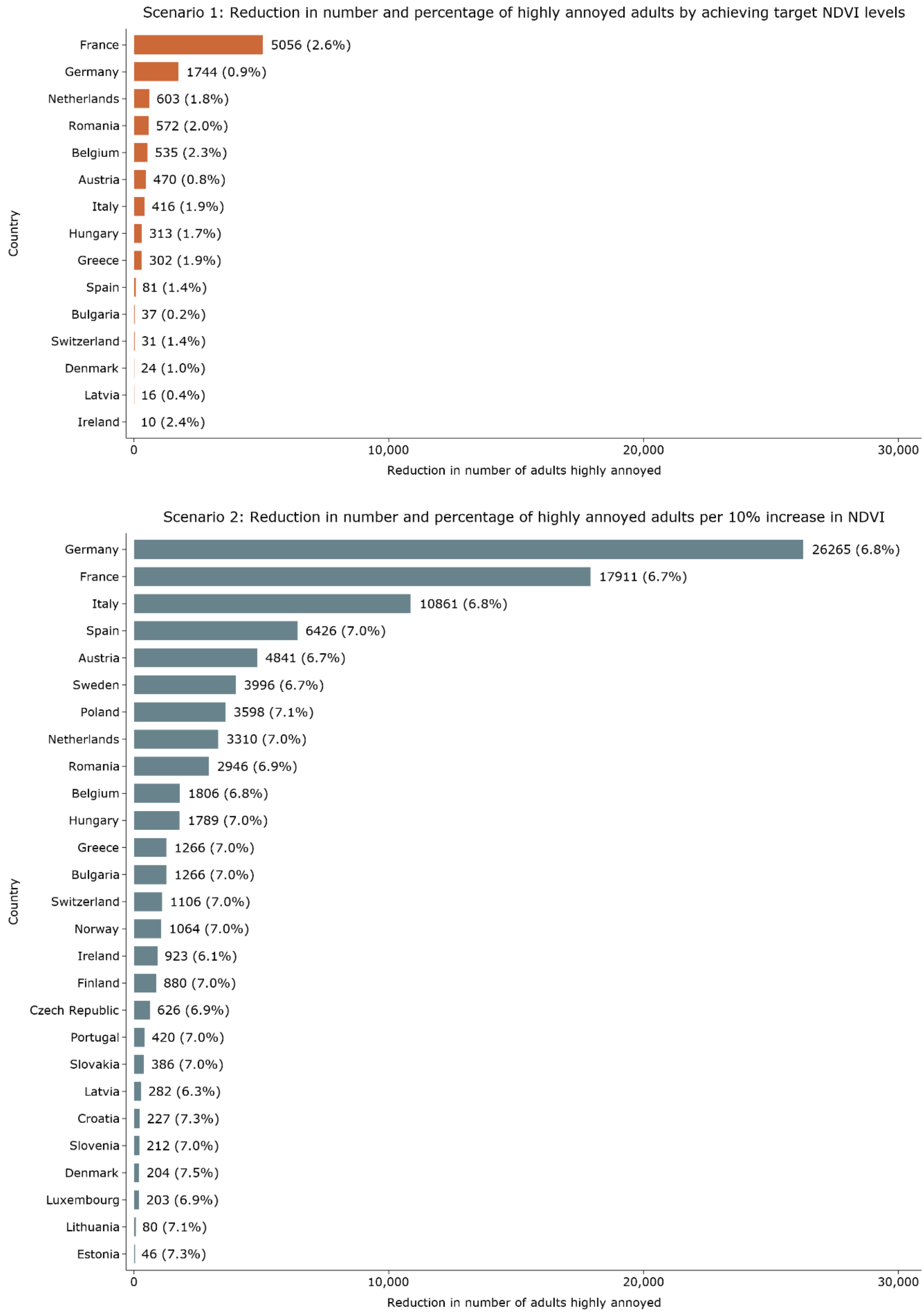
For railway noise, Germany has the largest potential reduction in annoyance, representing a reduction of 26,265 highly individuals (28.3% of the total reduction). This is followed by France (17,911, 19.3%), Italy (10,861, 11.7%), and Spain (6,426, 6.9%) (Figure 3.2). The top 10 agglomerations with the highest potential reduction are Paris and Lyon (France); Vienna (Austria); Berlin, Munich, Cologne, and Dusseldorf (Germany); and Rome, Genoa and Milan-Monza and Rome (Italy) (Annex 2).

Figure 3.1 Reduction in road traffic noise annoyance in urban areas by country



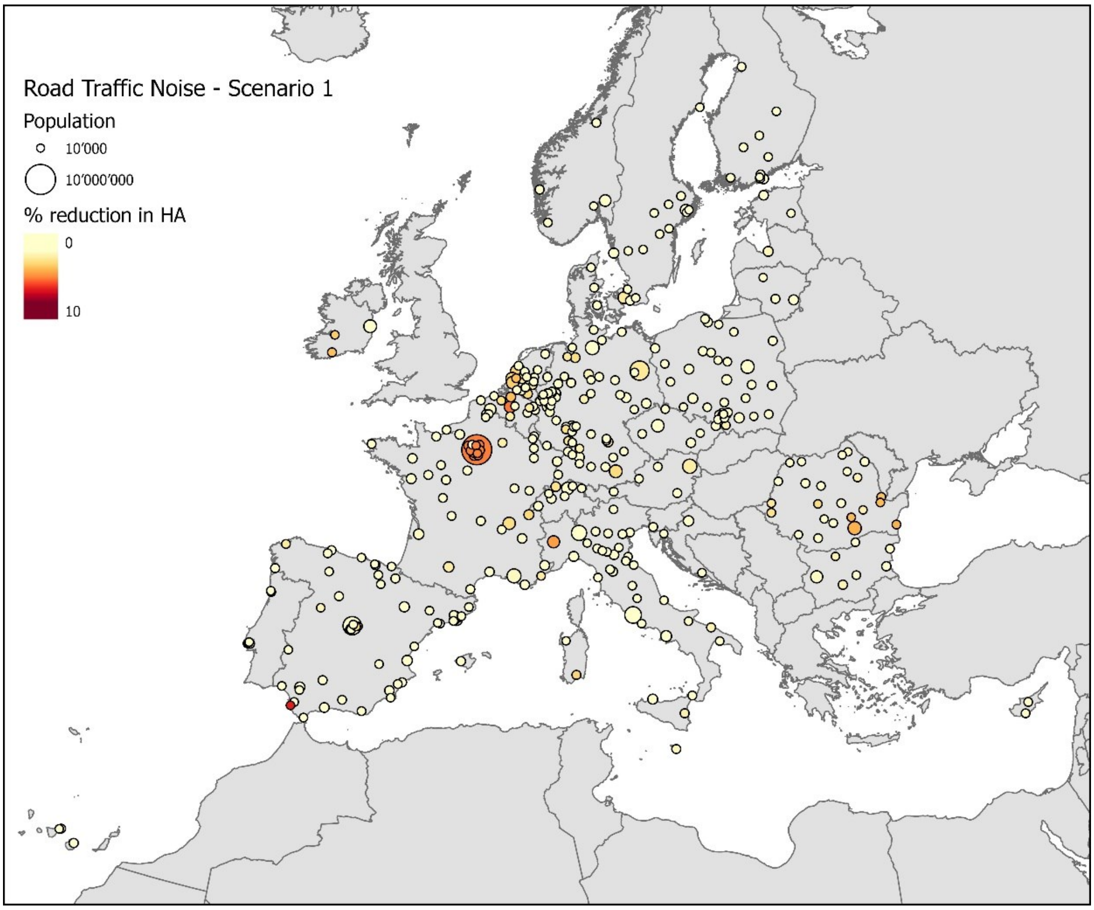
Note: In Scenario 1, agglomerations that already meet the WHO recommendation for universal access to green space are excluded from the calculations, as no additional benefit is assumed. Therefore, not all countries are represented in the figure.

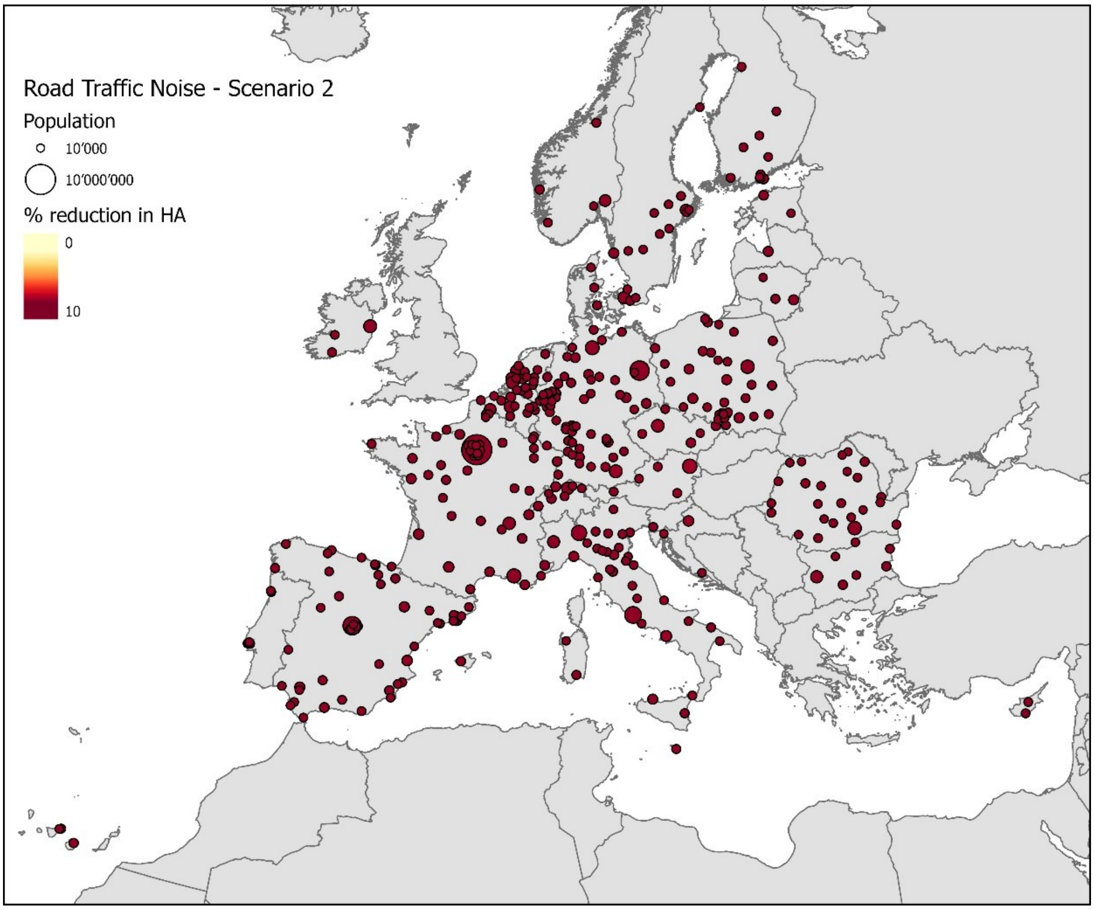
Figure 3.2 Reduction in railway noise annoyance in urban areas by country



Note: In Scenario 1, agglomerations that already meet the WHO recommendation for universal access to green space are excluded from the calculations, as no additional benefit is assumed. Therefore, not all countries are represented in the figure.

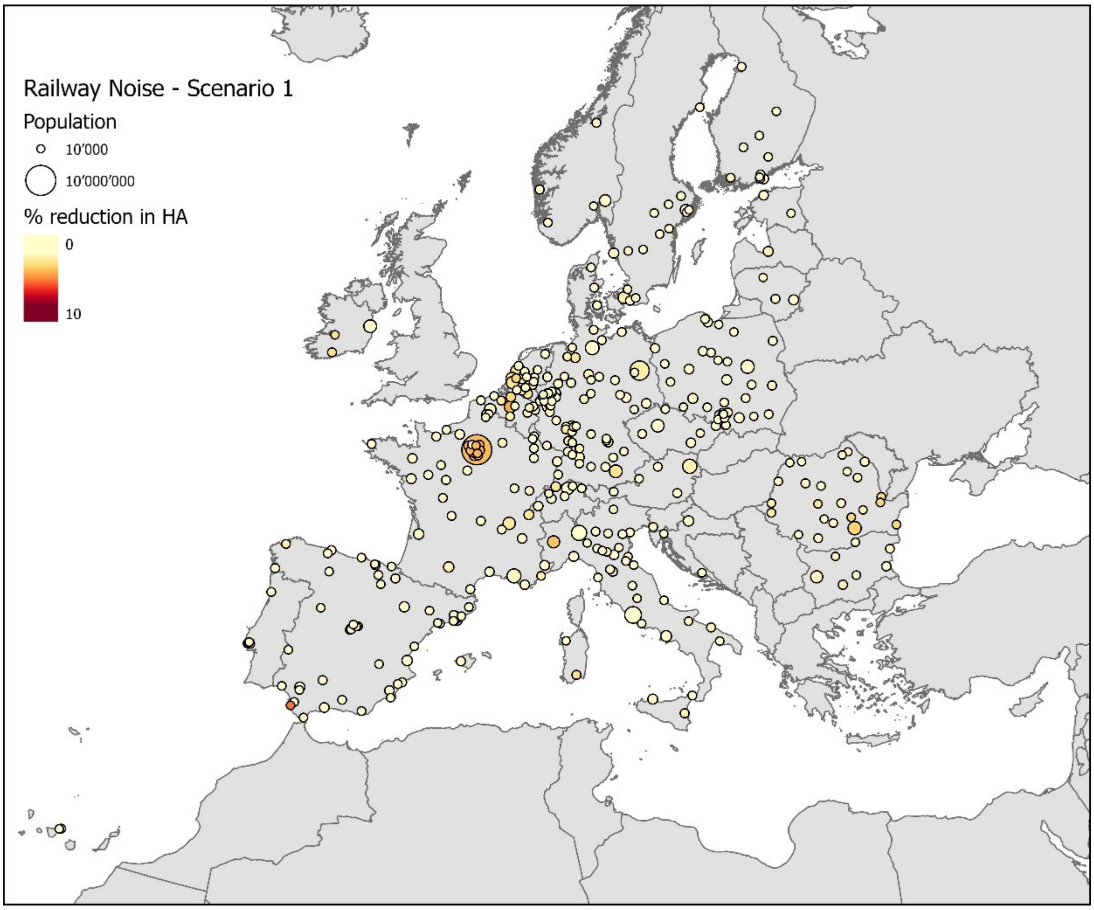
Map 3.1 Percent reduction of highly annoyed adults by agglomeration – road traffic noise

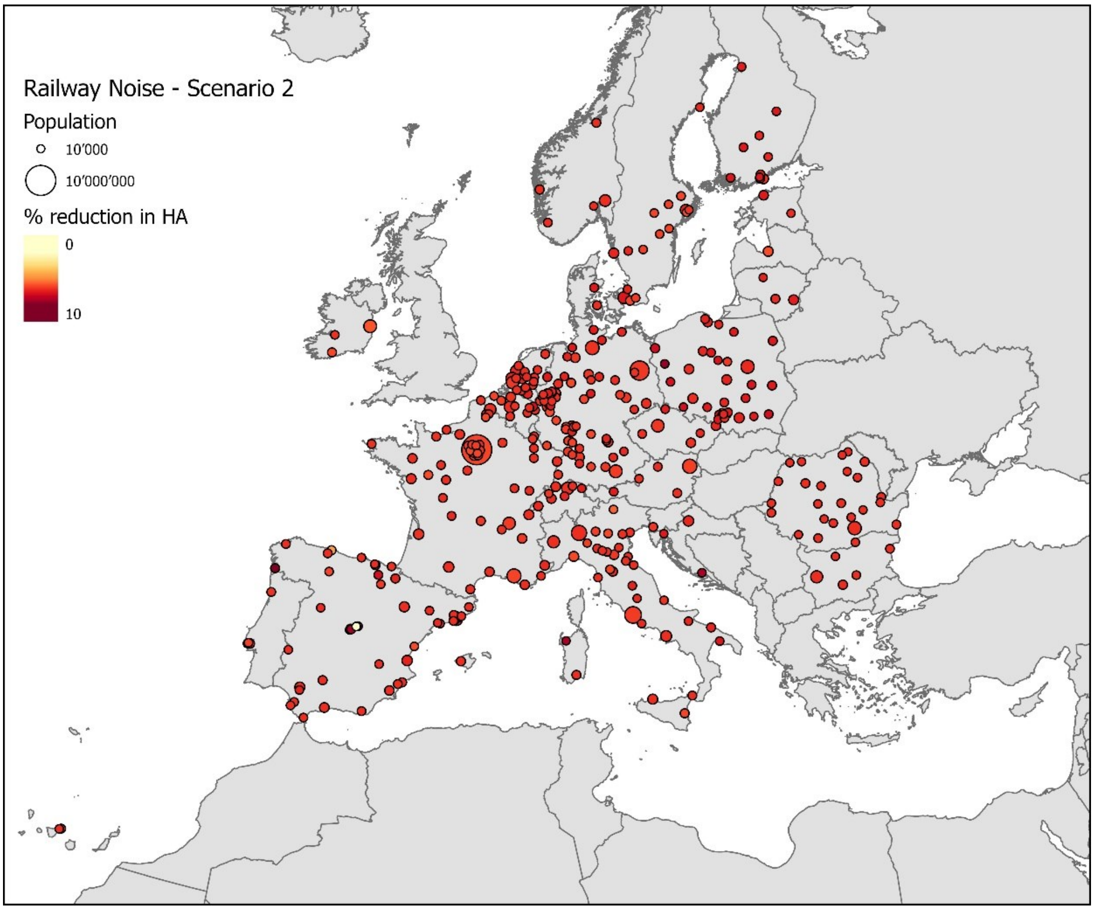




Note: The size of the circles on the map indicates the population size of the agglomerations.

Map 3.2 Percent reduction of highly annoyed adults by agglomeration – railway noise





Note: The size of the circles on the map indicates the population size of the agglomerations.

4 Discussion

4.1 Key findings

This report underscores the significant potential of increasing green spaces availability to mitigate noise annoyance in urban environments in Europe. The results of the narrative review and the health impact assessment highlight several critical points:

- **Consistent evidence of health benefits from quiet areas:** The narrative review provides compelling evidence that proxies of quietness, such as green spaces, are beneficial for health in particular in relation to type II diabetes, cardiovascular diseases, mental health issues, birth-related outcomes, cancer, and all-cause mortality.
- **Green spaces reduce noise annoyance**: Evidence from multiple studies indicates that individuals in areas with significantly more greenery and green spaces near and around their residence report lower annoyance levels despite exposure to higher noise levels (Table 2.2). The study using objective noise data observed an equivalent sound pressure difference of 6.3 dB for road traffic noise and 3.6 dB for railway noise when comparing areas with low vs. high amounts of residential green (5^{th} to 95^{th} percentile NDVI) (Schäffer et al., 2020).
- **Reductions in the number of highly annoyed people through increasing green spaces**: The health impact assessment showed that meeting WHO recommendations for universal green space access could reduce the number of people highly annoyed by road traffic noise by 1.1% and railway noise by 0.7%, preventing 1,149 and 112 DALYs, respectively (Scenario 1). An incremental NDVI increase of 10% across all agglomerations would lead to a more pronounced reduction—9.6% for road traffic noise and 6.8% for railway noise—preventing 9,709 and 1,022 DALYs, respectively (Scenario 2).
- **Regional differences in noise reduction potential**: In relation to the WHO recommendation for universal access to green spaces (Scenario 1), the potential for reducing noise annoyance varied across European agglomerations, influenced by baseline noise levels, population size, and the gap between current and target NDVI. For example, Paris stands out with the highest reduction potential due to its large baseline annoyance and a notable gap between its current NDVI (0.421) and target NDVI (0.475). In contrast, despite having the largest gap between current NDVI (0.155) and target NDVI (0.231) among all agglomerations, Cadiz, Spain, shows a smaller reduction potential because of its smaller population and lower baseline annoyance. In Scenario 2, which assumes a universal incremental increase in greenness, similar percentage reductions are observed across all agglomerations: approximately 9% reduction in road traffic noise annoyance and around 7% reduction in railway noise annoyance. Annex 2 highlights the top 20 agglomerations with the highest reductions in highly annoyed individuals under these scenarios.
- **Effectiveness of green spaces in reducing road traffic vs. railway noise annoyance:** The observed greater reduction in annoyance from road traffic noise compared to railway noise can be attributed to several factors. First, higher baseline exposure to road traffic noise creates a larger pool of highly annoyed individuals who benefit more from mitigation efforts. Additionally, road traffic noise typically exhibits a higher baseline level of annoyance and a more pronounced response to changes in noise levels; thus, even modest reductions are more noticeable. Finally, the assessment of a larger number of agglomerations for road traffic noise means that green space interventions have a broader impact, further amplifying the overall reduction in noise annoyance.

- **Green helps reduce noise annoyance, mainly in the lower noise bands:** The impact of green spaces on reducing noise annoyance varies with baseline levels of exposure (Annex 3). The health impact assessment quantified these effects for individuals exposed to noise above the END reporting threshold of 55 dB L_{den}. Significant reductions in annoyance are observed primarily in the lower decibel ranges, where the majority of the exposed population resides. As fewer people are exposed to higher noise levels, the effectiveness of green space interventions decreases.
- **This case study likely underestimates the health benefits of green spaces for reducing noise-related health effects:** First, the analysis only considered data from adults in 417 urban agglomerations (where 9,218,282 were highly annoyed by road traffic noise) and 396 urban agglomerations (where 1,364,867 were highly annoyed by railway noise), which is lower than previous estimates of noise annoyance in Europe. In 2017, it was estimated that 17,150,500 people were highly annoyed by road traffic noise and 3,497,100 by railway noise in Europe. Importantly, these prior estimates include individuals living outside urban areas, where around 25% of those annoyed by road traffic noise and 50% of those annoyed by railway noise reside—many of whom would also benefit from greener-quieter areas. Second, this study focused exclusively on reductions in noise annoyance by increasing availability of green spaces. There is substantial evidence suggesting that increased availability and accessibility to green spaces could prevent a broader range of noise-related health effects beyond annoyance, including reductions in the prevalence of type II diabetes, cardiovascular diseases, mental health disorders, and even all-cause mortality, though the quantitative data for these outcomes are currently lacking. Expanding future research to include these health outcomes could reveal even greater benefits from green space interventions.

While the report provides valuable insights, it is important to acknowledge certain limitations. The reliance on NDVI as the sole exposure metric, reflecting greenness, does not capture the quality and accessibility of green spaces. If the major benefit of green spaces is access to and spending time in parks and green areas, NDVI is a less useful measure. On the other hand, NDVI much more broadly captures total greenness within areas compared to land use maps because it measures the reflectance of all vegetation, including individual trees for example along streets, private gardens, and even green rooftops. These types of areas and features, beyond the typical urban green space, also act to dampen noise exposure for the local residents, and add to the visual aesthetic of neighbourhoods. Future research into the interactions between noise and green space exposure on health should incorporate more detailed green metrics, such as specific type of green and the spatial distribution of green areas.

Additionally, the cross-sectional nature of the primary studies included in the review limits the ability to draw causal inferences. Longitudinal studies are needed to better understand the long-term impacts of increasing green space on noise annoyance and related health outcomes. This report also does not explore the extent to which the health benefits are causally related to quietness versus other beneficial aspects of green space.

4.2 Mechanism of noise annoyance mitigation through green space exposure

Dense vegetation can act as physical barriers that intercept and absorb sound waves, thereby reducing noise propagation into adjacent areas. This acoustic buffering effect is particularly significant for low-frequency noises typical of road traffic and railway, where dense vegetation and natural features attenuate sound levels effectively (Ow and Ghosh, 2017; Aylor, 1977).

Beyond their acoustic properties, green spaces provide psychological benefits that contribute to noise annoyance reduction. Exposure to green environments has been shown to lower stress levels and enhance psychological restoration, influencing individuals' perceptions of noise. The presence of greenery creates a more pleasant visual and auditory environment, which can distract from or mask unwanted noise (Alvarsson et al., 2010). Additionally, access to green spaces encourages outdoor activities and social interactions, promoting community cohesion and reducing individual sensitivity to noise disturbances (Gidlöf-Gunnarsson and Öhrström, 2007; Markevych et al., 2017). The benefits of green spaces extend beyond noise annoyance mitigation and generally contribute to improvements in health. Living in or near green areas is associated with lower risks of cardiovascular diseases and better mental health due to reduced stress and increased physical activity (Keith et al., 2024). Additionally, green spaces enhance cognitive health and contribute to lower levels of depression and anxiety (Markevych et al., 2017). These benefits underscore the importance of incorporating green spaces into urban planning to promote healthier communities (Jimenez et al., 2021).

The type and design of green spaces also play a crucial role in noise mitigation. Natural features such as trees, shrubs, and green corridors enhance biodiversity while providing effective noise reduction benefits. Well-designed green infrastructure integrates diverse vegetation types and includes elements like sound-absorbing materials and water features, further enhancing their noise-mitigating capabilities (Pheasant et al., 2008).

4.3 Exclusion of aircraft noise

It is important to note that the current health impact assessment focused solely on road traffic and railway noise, excluding aircraft noise. This exclusion is informed by findings from Schäffer et al. (2020) which indicate that increasing residential green can paradoxically increase annoyance from aircraft noise. Schäffer et al. (2020) argue that aircraft noise is perceived as more intrusive and alien, particularly in green areas where residents expect tranquillity. The contrast between the presence of aircraft noise and the anticipated quietness of green areas may thus increase the level of annoyance. Because of the difficulty in escaping aircraft noise within green spaces, it is argued that green spaces may not be an adequate proxy for quietness for this specific noise source.

4.4 Green initiatives in Europe and considerations when implementing interventions to increase green spaces

Greening initiatives closely align with current EU and global policy objectives. For example, the European Commission's Biodiversity Strategy encourages cities with at least 20,000 inhabitants to develop ambitious Urban Nature Plans (European Commission, 2020). These plans include creating biodiverse and accessible urban spaces, such as forests, parks, gardens, urban farms, green roofs, walls, tree-lined streets, meadows, and hedges. The policy aims to bring nature back into cities and reward community action. Additionally, signatories of another initiative by the European Commission, the Green City Accord, pledge to conserve and enhance urban biodiversity by expanding and improving green spaces in cities (European Commission, 2021). This focus on urban greenery is also reinforced by the United Nations Sustainable Development Goal (SDG) 11.7, which calls for "universal access to safe, inclusive, and accessible green and public spaces" (United Nations, 2015).

To translate these policies into tangible benefits, many European cities, characterized by their consolidated historic urban environments and limited vacant land, are implementing innovative green interventions. One effective strategy is revitalizing former industrial sites into parks. For example, Essen's Zollverein Park, once a coal mine industrial complex, has been transformed into green public spaces (Emschergenossenschaft Lippeverband, 2021). Incorporating nature-based solutions, such as green roofs and vertical gardens, is another approach. As a part of the EU-funded research project Clever Cities, Malmö has integrated green roofs and living walls into its urban landscape, contributing to urban biodiversity and sustainability (Clever Cities Malmö, 2022). Additionally, reconfiguring traffic systems and reallocating road and parking spaces into green belts and ecological corridors, as seen in Vitoria-Gasteiz (Vitoria-Gasteiz City Council, 2014) and Barcelona's superblocks (Barcelona City Council, 2016), offers another viable strategy.

Integrating green infrastructure into cities provides opportunities to improve public health by reducing noise annoyance and lowering chronic disease risks (Jimenez et al., 2021; Twohig-Bennett and Jones, 2018). It also offers multiple co-benefits, enhancing urban resilience to climate change impacts (Zhang and Qian, 2024; Herath and Bai, 2024). For example, green spaces provide shade and lower high temperatures, thereby mitigating urban heat island effects. They also absorb storm water to reduce flood risks, improve air quality, sequester carbon, and increase biodiversity—all of which support environmental sustainability and help cities adapt to evolving environmental challenges.

Implementing interventions to increase urban greenery and green spaces requires careful consideration of various factors (WHO, 2017). These interventions may elicit responses from the community that differ from expected outcomes based solely on noise level reductions (Brown and van Kamp, 2017). Factors influencing community response include individual perceptions, social dynamics, and the broader socio-economic context of the neighbourhood. Contextual factors such as local environmental co-exposures (e.g., air quality, heat), neighbourhood characteristics (e.g., socio-economic status), and the perceived quality of the urban environment also shape the effectiveness of these interventions. Effective communication strategies and public engagement are crucial in garnering community support and ensuring the long-term sustainability of noise mitigation efforts through green space enhancements. Understanding these considerations are crucial for designing effective and sustainable strategies to enhance urban green infrastructure, mitigate noise annoyance, and promote overall urban health and well-being.

5 Conclusion

Enhancing quiet areas or dampening noise through strategic planting high vegetation in agglomerations presents a viable solution to mitigate noise annoyance and likely many other noise-related health effects. While increasing respites through quality parks and green spaces is one dimension of promoting quietness, other factors—such as pleasant sounds from water, wind, and wildlife, along with visually appealing natural elements—also contribute. The findings of this report advocate for the integration of quiet areas into urban planning and public health policies to foster healthier, more liveable and resilient cities.

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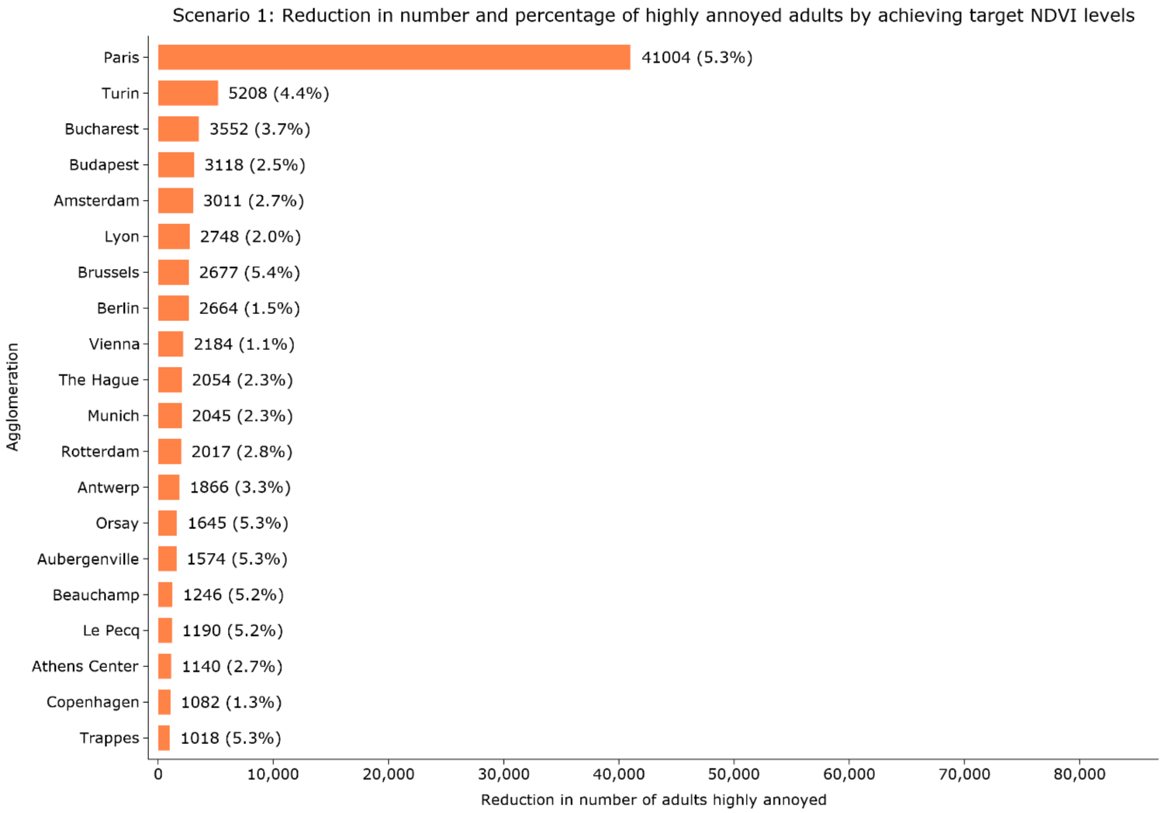
Annex 1

Table A.1 Search terms for the literature review on the effect of noise annoyance (reduction) in relation to green space

Exposure	"noise, transportation"[MeSH Terms] OR ("noise"[Title/Abstract] AND "traffic"[Title/Abstract]) OR ("noise"[Title/Abstract] AND "transportation"[Title/Abstract]) OR ("noise"[Title/Abstract] AND "road"[Title/Abstract]) OR ("noise"[Title/Abstract] AND ("airplane"[Title/Abstract] OR "aircraft"[Title/Abstract])) OR ("noise"[Title/Abstract] AND "rail*"[Title/Abstract]) OR ("noise"[Title/Abstract] AND "environmental"[Title/Abstract]) OR ("noise"[Title/Abstract] AND "community"[Title/Abstract])
	(("quiet"[Title/Abstract] OR "tranquil"[Title/Abstract]) AND ("area*"[Title/Abstract] OR "space*"[Title/Abstract] OR "environment*"[Title/Abstract])) OR "quietness"[Title/Abstract] OR "tranquillity"[Title/Abstract] OR "tranquility"[Title/Abstract]
	"green space*"[Title/Abstract] OR "green area*"[Title/Abstract] OR "green"[Title/Abstract] OR "greenery"[Title/Abstract] OR "greenness"[Title/Abstract] OR "urban green space"[Title/Abstract] OR "parks, recreational"[MeSH Terms] OR "park*"[Title/Abstract] OR “Normalized Difference Vegetation Index"[Title/Abstract] OR "NDVI"[Title/Abstract] OR "vegetation*"[Title/Abstract] OR "natural space*"[Title/Abstract] OR "natural environment*"[Title/Abstract] OR "naturalness"[Title/Abstract] OR "urban biodiversity"[Title/Abstract] OR "tree cover"[Title/Abstract] OR "street tree*"[Title/Abstract] OR "forests"[MeSH Terms] OR "forest"[Title/Abstract] OR "gardens"[MeSH Terms] OR "garden"[Title/Abstract]
Outcome	"annoyance"[Title/Abstract] OR "disturbance"[Title/Abstract] OR "nuisance"[Title/Abstract] OR "bother*"[Title/Abstract]

Annex 2

Figure A.1 Reduction in road traffic noise annoyance of the top 20 agglomerations



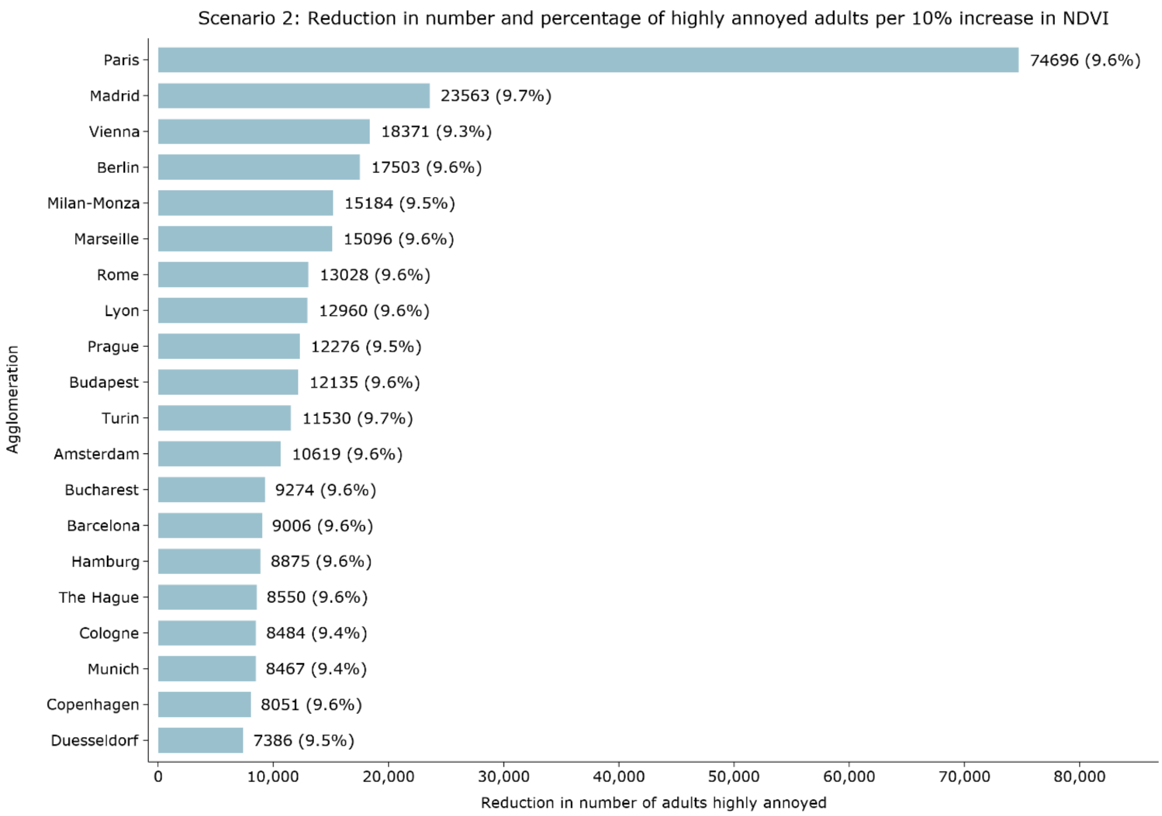
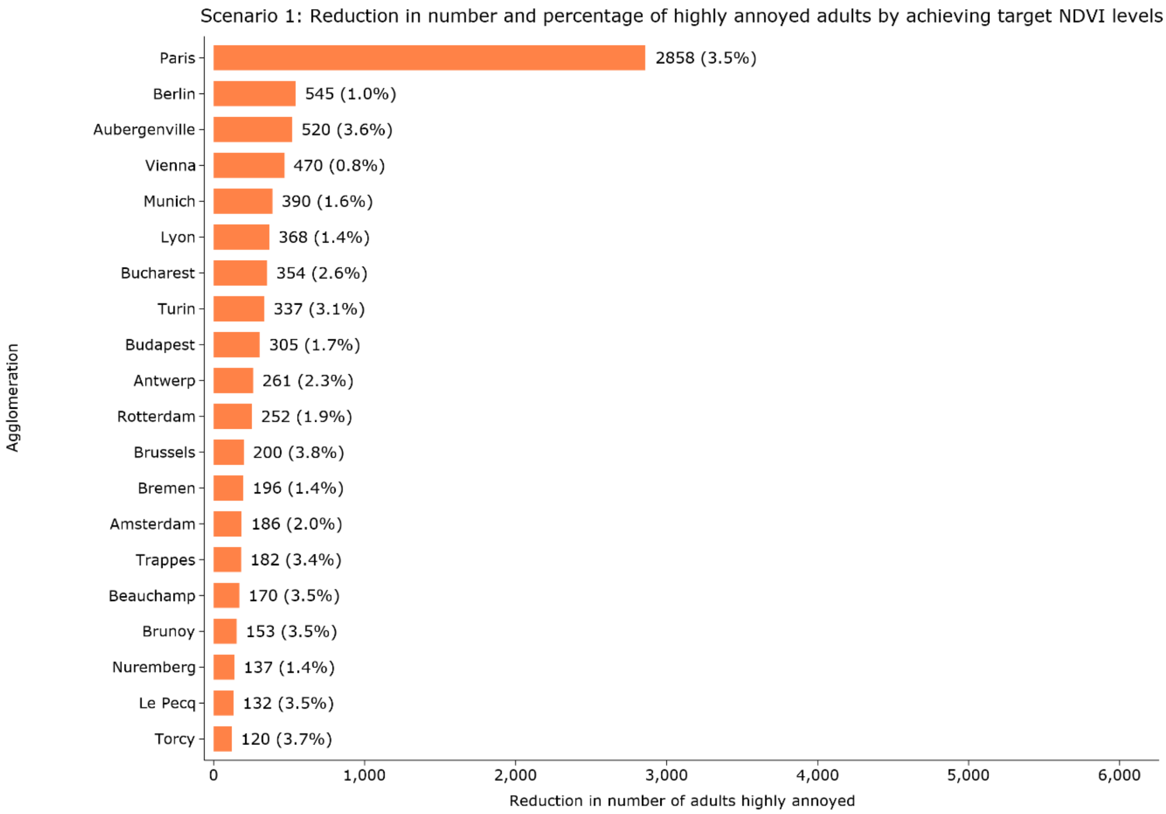
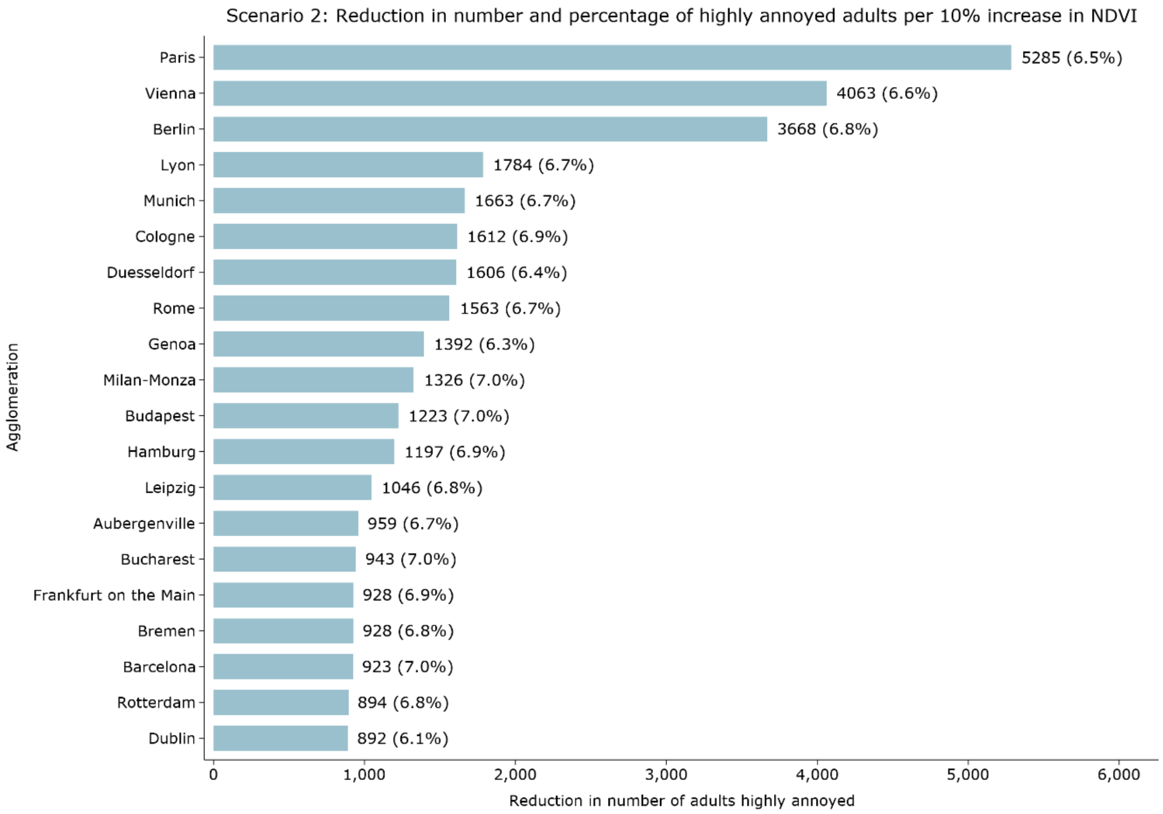


Figure A.2 Reduction in railway noise annoyance of the top 20 agglomerations





Annex 3

Figure A.3 Comparison of road traffic noise annoyance across noise bands and scenarios

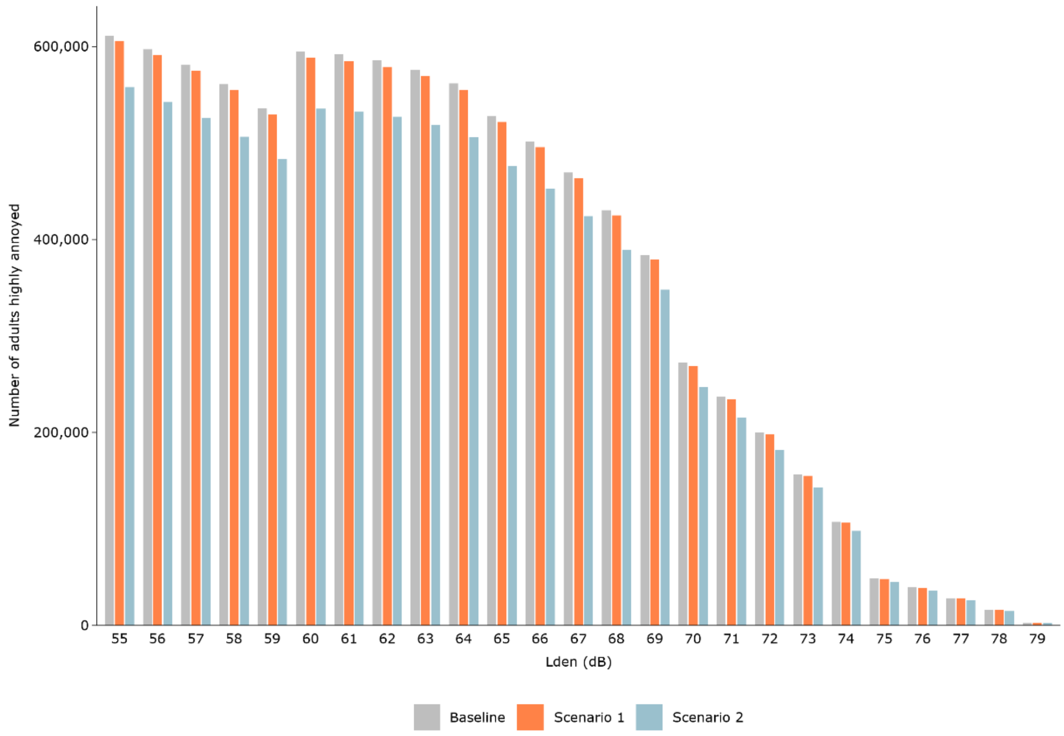
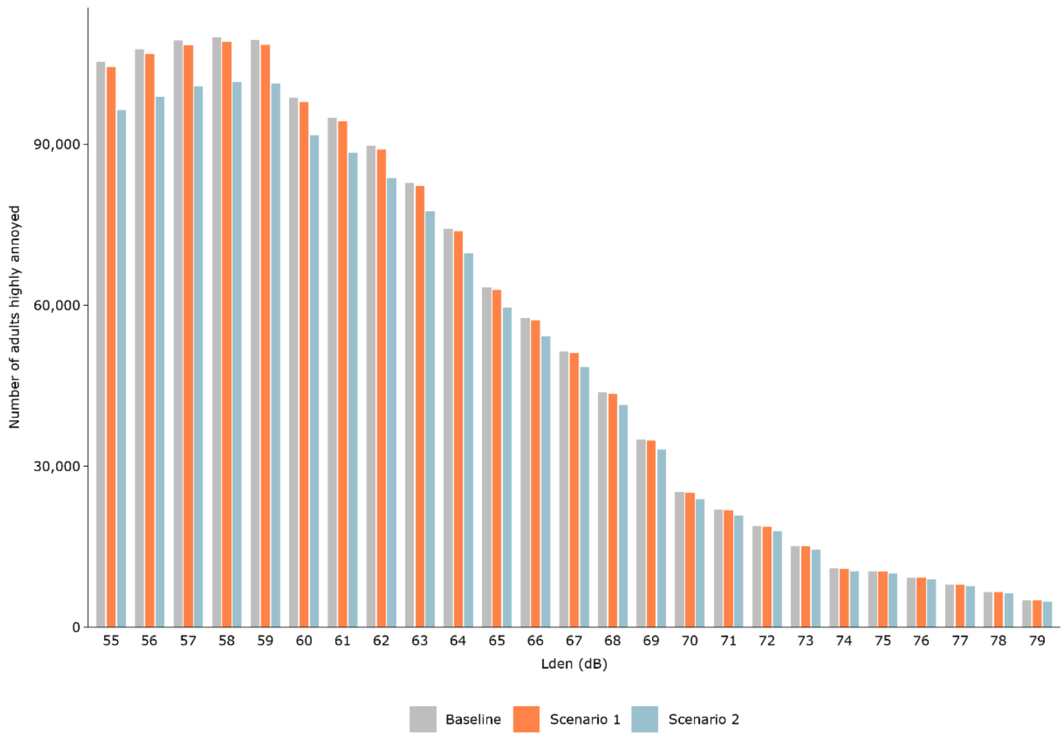


Figure 0. 1: Comparison of railway noise annoyance across noise bands and scenarios



List of abbreviations

Abbreviation	Name	Reference
dB	Decibel	
CI	Confidence interval	
DALYs	Disability-adjusted life-years	
EEA	European Environment Agency	https://www.eea.europa.eu/en
EIONET	European Environment Information and Observation Network	https://www.eionet.europa.eu/
END	Environmental Noise Directive	https://environment.ec.europa.eu/topics/noise/environmental-noise-directive_en
ERF	Exposure-response function	
ETC/HE	European Topic Centre on Human Health and the Environment	https://www.eionet.europa.eu/etcs/etc-he
EU	European Union	https://european-union.europa.eu/index_en
L_{den}	Day-evening-night noise level	
NDVI	Normalized Difference Vegetation Index	
pHA	Probability of high annoyance	
OR	Odds ratio	
RR	Relative risk	
WHO	World Health Organization	
%HA	Percentage of people highly annoyed	

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