Landscape and Urban Planning 263 (2025) 105452

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Assessing accessibility to quiet and green areas at the city scale using an agent-based transport model☆

Leonardo G. Luquezi [a,c,*], Valentin Le Bescond [b,c], Pierre Aumond [a,c], Pascal Gastineau [b,c], Arnaud Can [a,c]

[a] Univ Gustave Eiffel, CEREMA, UMRAE, F-44344 Bouguenais, France
[b] Univ Gustave Eiffel, AME-SPLOTT, F-44344 Bouguenais, France
[c] Institut de Recherche des Sciences et Techniques de la Ville (IRSTV), Ecole Centrale de Nantes, F-44321, Nantes Cedex 3, France

ARTICLE INFO

Keywords:
Agent-based models
Quiet areas
Accessibility metric
Environmental assessment
Noise modeling

ABSTRACT

Standard European approaches to assessing environmental noise focus on individuals exposed to critical noise levels. However, there are complementary approaches that question the accessibility of the population to quiet areas, highlighting the restorative properties of natural and quiet spaces for human health. In this regard, from an agent-based model, this study proposes a spatio-temporal methodology to assess accessibility to quiet areas in agglomerations, integrating everyday mobility into the analysis of place effects and opportunities. The two primary objectives are to identify current quiet areas that are accessible in order to preserve them acoustically and to identify green spaces with the greatest potential for accessibility in order to improve them acoustically. Green spaces of Lyon and Villeurbanne (France) are assessed during the lunch break period using an open-source framework. The results indicate that on average about 30% of agents have access to a quiet area. Further, green spaces in courtyards represent the current quiet areas with the greatest accessibility. Concerning spaces with great potential for accessibility, linear green spaces along rivers and small squares near high-attended urban centers represent the greatest potential gain in accessibility to quiet areas. Improvements pertain to the utilization of in-situ surveys to integrate human perception and place attendance evaluations in the formulation of action plans.

1. Introduction

Noise models represent the central element in the standard assessment of noise exposure and its human health impacts in Europe (European Commission, 2015). The number of individuals exposed to critical noise thresholds is determined by modeling sound levels at the facades of residences and the number of residents in these facilities. However, this approach has limitations as it does not consider exposure as a dynamic process, that is, the spatial presence of individuals is static, neglecting everyday mobility, and the estimated sound levels are based on yearly energetic averages, neglecting noise dynamics and intermittency.

To expand the static and residential exposure concept to the broader concept of exposure process (Fenger, 1999), spatio-temporal model techniques are essential. On the one hand, these techniques are required to model the evolution of daily activities and trajectories of individuals. On the other hand, they are required to model the evolution of the acoustic environment conditions. The combination of these temporal-dependent pieces of information accurately reflects the complexity of the noise exposure process in urban environments.

Agent-based modeling is a promising spatio-temporal model technique for enhancing environmental exposure assessments (Gastineau et al., 2023). In particular, agent-based transport models combined with environmental acoustic models can simulate the everyday mobility pattern of a population and the noise levels resulted from its transport-related noise emissions (Cucurachi, Schiess, Froemelt, & Hellweg, 2019; Houot, Antoni, Pujol, Lamiral, & Mauny, 2015; Kaddoura, Kröger, & Nagel, 2017; Le Bescond, Can, Aumond, & Gastineau, 2021). In this context, the agents of a modeled population are understood as individual travelers performing their planned activities during a typical weekday (activity-based model).

The dynamic simulation of the activity trajectory of agents enables the dynamic characterization of noise emissions and propagation. Then, based on dynamic noise maps and agents' activity location, the noise exposure profile of each agent is estimated, providing

☆ This document is the results of the research project SYMEXPO funded by the French National Research Agency (ANR).
* Corresponding author at: Univ Gustave Eiffel, CEREMA, UMRAE, F-44344 Bouguenais, France.
E-mail address: leonardo.galassi-luquezi@univ-eiffel.fr (L. G. Luquezi).

https://doi.org/10.1016/j.landurbplan.2025.105452
Received 9 September 2024; Received in revised form 10 June 2025; Accepted 14 July 2025
Available online 28 July 2025
0169-2046/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

insights into when, where, and to what extent agents are affected by noise (Le Bescond et al., 2021; Luquezi, Le Bescond, Aumond, Gastineau, & Can, 2025). Additionally, because the modeled population is statistically representative of the census survey, agent-based models can be used to assess which socio-economic groups are most affected by noise exposure (Gurram, Stuart, & Pinjari, 2019; Nygren et al., 2024). Despite their potential, these exposure frameworks are still under development, and their current limitations have been discussed in recent studies (Bastarianto, Hancock, Choudhury, & Manley, 2023; Luquezi, Le Bescond, Aumond, Gastineau, & Can, 2024a; Sonnenschein, Scheider, de Wit, Tonne, & Vermeulen, 2022).

Agent-based exposure models have primarily centered on individuals exposed to high noise levels and its adverse impacts on human health. Nevertheless, there are complementary methods in environmental acoustics that can be improved with consideration of population mobility, and merit scientific attention. In particular, that is the case for assessing the environmental opportunities of a population in accessing quiet areas (Battaner-Moro, Barlow, & Wright, 2010; De La Maza, Blanes, Ubach, Fons, & Ramos, 2019; European Environment Agency, 2014).

Quiet areas can be understood in terms of places undisturbed by unwanted sounds generated by human activities (European Commission, 2002). Environmental noise interferes with communication, e.g., orientation, speech, and warning signals, and disrupts cognitive processes, e.g., sleeping, thinking, reading, writing and learning (Stansfeld et al., 2005; World Health Organization, 2011). Therefore, the objective of preserving quiet areas is to preserve places that provide human health benefits. In particular, quiet areas are associated with restorative benefits, such as attention restoration and stress reduction (Payne & Bruce, 2019; Shepherd, Welch, Dirks, & McBride, 2013). In addition, these spaces have a positive economic value, as their contribution to health improvements leads to a reduction in the socio-economic costs of noise impacts.

In urban environments, green spaces are particularly important candidates for quiet areas. Research has shown that urban green spaces support the restorative process in humans (Kaplan, 1995; Ulrich et al., 1991), contribute to the physical and mental health of the population (Jackson, 2003; Takano, Nakamura, & Watanabe, 2002) and play an important role in supporting diverse social activities (Barbosa et al., 2007). The restorative process in green spaces is related to the presence of natural sounds and quietness (Alvarsson, Wiens, & Nilsson, 2010). When appropriately planned, green spaces can provide quiet areas with excellent acoustic properties, and the level of noise satisfaction in these spaces has a significant impact on the overall users satisfaction (Rey-Gozalo, Barrigón Morillas, Montes González, & Atanasio Moraga, 2018; Rey-Gozalo, Barrigón Morillas, Montes González, & Vílchez-Gómez, 2023). Furthermore, the preservation of quiet areas can benefit biodiversity from the perspective of limiting biodiversity loss related to habitat destruction and fragmentation (European Environment Agency, 2014).

The benefits of quiet areas are only achieved if these spaces are accessible to the population. Accessibility is a relevant indicator to evaluate the effective social and ecological functioning of cities (James et al., 2009). Easy access is a relevant factor when promoting relief from environmental stress and opportunities for relaxation (Gidlöf-Gunnarsson & Öhrström, 2007). Furthermore, an increase in urban green spaces does not necessarily lead to greater accessibility (Chen & Chang, 2015), particularly when these areas are located far from population centers.

The first European directive to address the issue of quiet areas was the 2002 Environmental Noise Directive (European Commission, 2002). This directive underscores the importance of protecting quiet areas, segmenting them into those in the open countryside and those in urban areas. These areas should respect environmental noise conditions designated by the competent authority, which is responsible for defining the limit values and appropriate noise indicators for assessing quiet areas. The Environmental Noise Directive did not provide an exact definition of quiet areas, leaving room for interpretation. European countries, cities, and regions have their definitions of quiet areas and their criteria for designating them (Peris, 2020). These criteria and definitions employed vary, but they encompass three main factors: the acoustic conditions, the landscape features (non-acoustic attributes), and the human perception evaluation of the studied areas.

In addition to physical acoustic indicators, human perception is crucial in assessing the acoustic quality of environments (Aletta, Oberman, & Kang, 2018; Brown, Gjestland, & Dubois, 2016; Filipan et al., 2017). Aletta, Kang, and Axelsson (2016) explored how soundscapes are assessed and measured, focusing on key descriptors and developing predictive models for soundscape studies. Their work emphasized the need for selecting the right descriptors, such as affective qualities (e.g., pleasantness, eventfulness), and the importance of contextual evaluation of the acoustic environment. Unfortunately, human perception is frequently overlooked despite its significance in the designation process of quiet areas.

This study proposes an innovative spatio-temporal assessment framework of quiet areas accessibility. The assessment is formulated using an agent-based model to estimate environmental opportunities for agents along their activity trajectory. On the one hand, the designation of quiet areas is informed by dynamic environmental noise conditions, which are estimated from the simulation of transport-related traffic on a typical working day. On the other hand, the accessibility of agents to these spaces is assessed by analyzing their simulated trajectories, taking as a spatial reference the location of the various activities carried out throughout the day. In this way, the temporal evolution of accessibility to quiet areas is assessed by integrating daily mobility into the study of place effects, highlighting the importance of time in shaping health restorative opportunities within places (Vallée, 2017).

The environmental opportunities of a population are analyzed through a case study of the Lyon Metropolitan Area (France). The case study focuses on the accessibility to quiet areas during the lunch break period between 12:00 and 14:00. The framework is implemented with two analytical objectives: to identify the current quiet areas that are accessible with the objective of preserving them acoustically, and to identify the green spaces with the greatest accessibility potential with the objective of improving them acoustically.

In Section 2, the agent-based approach developed to assess the accessibility to quiet areas is described and the Lyon and Villeurbanne exemplification case study is presented. In Section 3, the results of the accessibility to the current state of quiet areas, and the maximum potential of quiet areas are analyzed. In Section 4, the model and methodology limitations, as well as further investigations are discussed. Finally, in Section 5, a conclusion is drawn with the principal contributions of the study.

2. Material and methods

2.1. Agent-based models for accessibility to quiet areas

Agent-based modeling is an emerging technique that is distinguished by the representation of autonomous entities that are capable of making choices and learning. Agent-based models for transport simulation aim to represent the everyday mobility and activity needs of a population. The transport demand data is modeled as a synthetic population, defined as a set of agents each with an activity plan. An activity plan is a sequence of daily activities, with their respective location, initial start time, duration, and mode of transportation to reach them. The synthetic agents are modeled to statistically represent a population based on census surveys and the mobility behavior of a typical working weekday based on household travel surveys.

In the context of the simulation, agents of a synthetic population pursue their activity plans in a competitive environment within a transportation system with limited supply resources, e.g. limited public

transport lines and road capacity. At the end of the simulation, the trajectory of each agent is estimated. Concurrently, the traffic conditions observed on transport networks are the consequence of the collective travel patterns manifested by the modeled population.

The data concerning traffic flows is utilized in an acoustic model to estimate environmental sound levels. The aggregation of traffic conditions over time intervals enables the dynamic characterization of noise emissions, while the calculation of noise propagation enables the generation of noise maps (Le Bescond et al., 2021). These maps facilitate the visualization and quantification of environmental noise, thereby permitting the designation of areas protected from transport-related noise.

The estimation of both the everyday mobility of a population and the consequent environmental noise conditions provides a foundation for the study of opportunities for agents to access quiet areas. A cross-referencing of the spatio-temporal evolution of the location of agents and the designated quiet areas serves to assess the accessibility of the modeled population.

Prior to the elaboration of the accessibility assessment methodology employed in this study, a comprehensive understanding of the model and tools utilized is imperative.

2.2. Framework tools

In this study, the agent-based framework utilized is formulated based on three tools, EQASim, MATSim, and NoiseModelling. This framework is representative of the current literature and has been explicated and utilized in prior research publications (Hankach et al., 2024; Le Bescond et al., 2021; Luquezi et al., 2024a; Nygren et al., 2024). It is important to highlight that the entire framework only utilizes open-source tools and open data.

2.2.1. Transport modeling

Two tools are used to build the transport model: EQASim[1,2] (Hörl & Balac, 2021b), which models a synthetic population, i.e. a set of agents with an associated activity plan, and MATSim,[3] (Axhausen, Horni, & Nagel, 2016) which is an agent-based transport simulator compatible with the synthetic population generated previously.

In the process of generating a synthetic population, a statistical matching algorithm between an agent modeled from the census survey and an individual from the household travel survey is used to assign activity plans to agents. The matching is based on a specific set of attributes: age group, sex, socio-professional category, employment, education, region of residence, and car availability.

Agents are described by personal attributes (e.g. age, sex, ongoing employment, education status, and possession of a driver's license), household attributes (e.g. number of people, household income), and neighborhood attributes (e.g. neighborhood location), as well as an activity plan. The activities that agents can perform are classified into six categories: work, study, leisure, home, shop, and others.

Once the agent has an activity plan, the definition of the activity locations of agents is done through a large-scale destination choice model. Essentially, the algorithm distinguishes primary location assignment, i.e. home, work, and study, from secondary location assignment, i.e. shop, leisure, and others, when assigning their place of performance. The location assignment is supported by data regarding work and study commuting, and data on transportation mode usage to maintain coherence with real mobility practices (Hörl & Axhausen, 2023; Hörl & Balac, 2021a).

Enterprise census, addresses, service, and facility databases are utilized to model real residential and activity locations. In the address database, each address is associated with a specific point in space, typically corresponding to the entrance of the house or building. Then, a data treatment is conducted to differentiate the types of activities associated with each address, e.g., home, work, study, etc. Therefore, the allocation of activity locations to agents is executed at the facility scale.

The transport mode categories simulated are private car, public transport (bus, train, tram, etc.), cycling, and walking. The traffic model implemented is mesoscopic, based on first-in-first-out queues and the traffic flow represents an average traffic behavior (Axhausen et al., 2016). Vehicles travel at constant speeds, without acceleration, and other detailed vehicle dynamic behaviors. At the simulation stage, an algorithm runs through iterations during which agents can change their mode and itinerary to improve the performance of their activities. The traveling choices made by the agent are based on a discrete mode choice module.

In terms of validation, the synthetic population process is developed to preserve the main statistical properties of the transport demand and mobility behavior. Common validation analyses relate to the socio-demographic structure of the population, the population residential spatialization, the structure of synthetic daily plans of the agents, the comparison of commuting patterns and flows, and the distance distribution from and to secondary activities by mode, among others. For more information, previous studies have described this agent-based framework in detail (Hörl & Axhausen, 2023; Hörl & Balac, 2021a, 2021c).

2.2.2. Environmental acoustic modeling

The tool used for the acoustic modeling is NoiseModelling[4] (Aumond, Fortin, & Can, 2020; Bocher, Guillaume, Picaut, Petit, & Fortin, 2019), which is an environmental acoustics platform that allows the implementation of CNOSSOS (European Commission, 2015) to generate noise maps. The simulated data on traffic conditions resulting from the mobility of agents are employed in the acoustic model for the estimation of noise emission and propagation.

At the noise emission step, the transport-related noise sources are characterized. Considering the volume of traffic, the speed of vehicles, the road geometry, the surface cover, and the type of traffic flow, among other parameters, the noise model estimates the noise emission level in each network segment. At the propagation step, the noise model simulates how sound waves propagate, reflecting off surfaces or diffracting around obstacles in space. To do so, the road network is divided into several point noise sources. The propagation paths from the sources to a given receiver, e.g., a receiver at a façade of a building, are computed. Considering each sound path, the contribution of each sound source emission is calculated, and then energetically summed into the corresponding receiver. With a set of receivers distributed throughout a given space, it is possible, for example, to generate noise maps.

Some relevant parameters of the acoustic model are: the absorption properties of the ground and road surfaces, the topography, the meteorology conditions, the presence of tunnels or noise-abatement infrastructures, the shielding effect of buildings, and the description of the vehicle fleet.

Due to the dynamic nature of agent-based transport models, it is possible to estimate dynamic noise maps of the acoustic environment by aggregating the transport traffic in several time intervals. Therefore, the acoustic environment is dynamically described, which allows the designation of quiet areas and their evolution over the study period.

The mesoscopic traffic resolution of agent-based models is adapted to estimate aggregated energy indicators, such as equivalent sound levels. Furthermore, because 15-minute intervals are considered sufficient to distinguish the period of the day (Brocolini, Lavandier, Quoy, & Ribeiro, 2013), this time interval is used for dynamically estimating equivalent sound levels of transport traffic.

[1] github.com/eqasim-org/ile-de-france, version 1.2.0.
[2] github.com/eqasim-org/eqasim-java, version 1.3.1.
[3] github.com/matsim-org, version 13.0.
[4] github.com/Universite-Gustave-Eiffel/NoiseModelling, version 4.0.3.

Table 1
Parameters of the acoustic model of the Lyon Metropolitan Area framework.

Parameter	Description/Value
Method	CNOSSOS
Maximum source distance	750 m
Maximum reflection distance	50 m
Reflection order	1
Vertical diffraction	Disabled
Horizontal diffraction	Enabled
Absorption by the ground	Fully reflective
Topography	Homogeneous (flat land)
Meteorology	50% favorable occurrence (all directions)
Tunnels	Neglected
Road surface	Fine broomed concrete (NL08)
Buildings (shielding effect)	Enabled (OpenStreetMap)
Noise sources	Road traffic (car and bus)

In the present version of the framework, private cars and buses are the sound sources considered for the acoustic model. These transportation and mechanic-related noises are characterized by high capillarity in urban networks. Noise from air and rail transport is neglected. The relief of the study area is also neglected. The acoustic absorption by the ground is kept by default, i.e. ground is fully reflective. The meteorology conditions are set to 50% of favorable occurrence in all directions. Table 1 summarizes the main parameters of the acoustic model. Further details on the assessment of noise based on this agent-based transport framework can be found in Le Bescond et al. (2021).

2.3. Definition of quiet areas accessibility

To assess accessibility, it is necessary to define an accessibility metric; the purpose of this metric is to measure whether individuals have access to a quiet area, i.e., whether they could potentially benefit from that area.

A metric to assess the accessibility to quiet areas can be formulated in three steps: First, eligible locations of interest that could be quiet areas must be defined; Second, the environmental acoustic conditions required to designate a quiet area must be defined; Third, an access metric must be defined to translate the nearby linkage between quiet areas and individuals.

2.3.1. Defining urban spaces eligible for analysis

In urban environments, quiet areas may be found in parks, in building courtyards, in gardens, in leisure areas, in school playgrounds, in private yards, in pedestrian streets, etc. The urban spaces eligible for analysis depend on the objective of the study. At this stage, the emphasis lies on landscape and land use characteristics of places.

The scope of environmental acoustics pertains to urban spaces in a comprehensive sense, considering the formulation of public policies for the population and the intervention of competent authorities. Accordingly, the primary focus of this study is on outdoor, public, and open spaces, excluding particular cases such as school playgrounds or private spaces that are of interest to specific groups.

When it comes to acoustic environments with benefits for human health, green spaces particularly stand out (Payne & Bruce, 2019; Van Renterghem, 2019). The presence of nature and natural sounds are understood as elements that promote the recovery of attention and stress reduction. Furthermore, urban green spaces contribute to the physical and mental health of the population (Jackson, 2003; Takano et al., 2002) and play an important role in supporting diverse social activities (Barbosa et al., 2007).

In this context, the focus of this study is on analyzing urban, open, outdoor, public, and green spaces. Operationally, the urban spaces identified are provided by local authorities, and the database utilized is a metropolitan database of parks and gardens. Further details regarding this database can be found in Section 2.5.

2.3.2. Defining acoustic conditions of quiet areas

An eligible urban space is designated as a quiet area if it meets certain acoustic conditions. In the context of assessing urban green spaces, noise emerges as the preeminent factor, with road traffic consistently identified a common predominant source of noise within these environments (Rey-Gozalo et al., 2018).

As previously stated in Section 1, the criteria for defining quiet areas are currently diverse (Peris, 2020). The selection criteria for quiet areas include L_{day} levels lower than or equal to 45 to 55 dB(A), L_{den} levels lower than or equal to 50 to 55 dB(A), among others (European Environment Agency, 2014).

The selection of the acoustic criteria must be determined in consideration of the acoustic resolution of the modeling framework. Here, the acoustic model is adapted to dynamically estimate acoustic energy indicators, e.g. equivalent sound levels. Therefore, the acoustic condition of quiet areas is defined by a transport noise threshold.

As this study focuses on the daytime period, areas with an equivalent sound level of less than 50 dB(A) over a time interval of 15 min are designated as quiet areas. This means that the quiet areas considered are sub-zones of the green spaces that have respected an acoustic condition over a period of time. To ensure the reliability of the designation, only areas with a minimum size of 100 m^2 are considered. This size is deemed sufficient to accommodate individuals and to prevent the inclusion of small, discontinuous, and isolated areas within the definition of quiet areas. These values are established under the European Environmental Agency good practices (European Environment Agency, 2014).

2.3.3. Defining an access metric

The access metric is generally delineated in terms of the distance or travel time between the location of an individual and the place of interest. This is due to the significance of physical proximity for accessibility (Irvine, Warber, Devine-Wright, & Gaston, 2013).

Active accessibility, especially walking accessibility, is considered a key indicator of nearby linkage between green spaces and human health (Ekkel & de Vries, 2017; Vale, Saraiva, & Pereira, 2016). Walking is the most common form of non-motorized transportation, and the incorporation of walking times in accessibility metrics is instrumental in ensuring that transportation systems are inclusive and cater to all residents, irrespective of their mobility restrictions, such as car ownership (Lanza, Pucci, & Carboni, 2023). Moreover, walking promotes physical activity and confers environmental benefits in comparison to motorized modes of transportation. In the (European Environment Agency, 2001) report, the measurement of citizen access to nearby public open areas is based on the indicator of "within 15 minutes' walk". In recent reports, (Martinuzzi & Lahoud, 2020), the indicator of "within 5 min walk" has been adopted.

In this study, the proximity metric is defined by the walking travel time between the activity location of the agent and the quiet areas. Considering the existing pedestrian network (OpenStreetMap), the potential locations to which an agent may have access are based on a maximum travel time of 5 min, and an average walking speed of 4.5 km/h, which corresponds to a distance of 375 meters following the pedestrian network. The agent's location is defined as the location of his longest activity in the 15-minute time interval considered. If the longest activity is travel between activities, no specific location is assigned to the agent. In operational terms, the implementation of the proximity metric for a given quiet area is estimated from its service area. Given a quiet area and a pedestrian network, the service area is the entire zone accessible on foot according to a specified time threshold, e.g. the 5-minute service area represents all the places from which a quiet area is accessible in less than 5 min.

The open-source OSMnx library[5] (Boeing, 2017), is employed to calculate service areas for quiet areas. Initially, for a quiet area polygon situated within a green space, its reference points are identified.

[5] github.com/gboeing/osmnx, version 1.9.3.

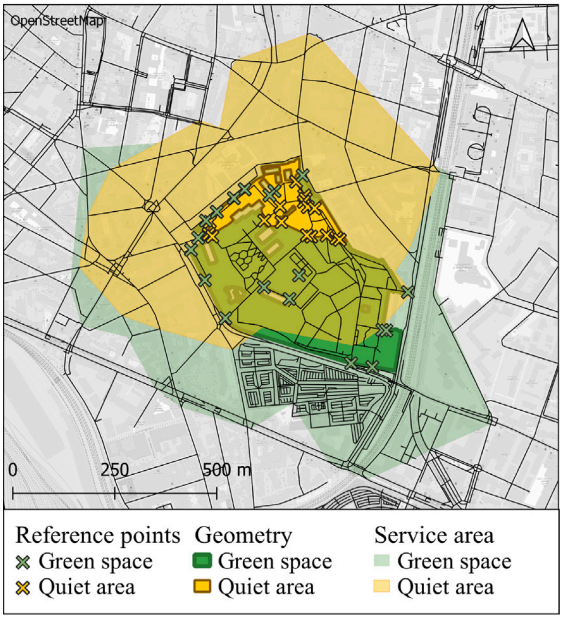


Fig. 1. Service areas of green space and its quiet area for a 5-minute walk at 4.5 km/h.

These reference points are the centroid of the quiet area polygon and the points of intersection between the edge of the polygon and the pedestrian network. The intersections represent the entrance channels to the quiet area, and the centroid is used because some small areas do not have an intersection with the network. Subsequently, all nodes of the pedestrian network that can be reached within the maximum travel time from the aforementioned reference points are identified. These nodes constitute the edge of the service area of the quiet area.

Fig. 1 illustrates the service area algorithm, delineating the service area of green space and its quiet area, as well as the reference points utilized to estimate them. The pedestrian network data is sourced from OpenStreetMap.[6]

It is essential to maintain consistency between the accessibility of the quiet area and the accessibility of the green space to which it belongs. This implies that the service area of the quiet area must always be contained within the service area of the green space. To ensure this consistency, the reference points of the quiet area are associated with the nearest reference point of the green space. The service area of the quiet area is determined based on these green space reference points.

To summarize the accessibility metric applied in this study, the urban spaces eligible for quiet areas are green, open, and public spaces of the study area. Quiet areas are designated for each 15-minute interval according to their acoustic conditions, i.e. LAeq,15 min value lower than 50 dB(A). Agents with access to a quiet area are distinguished based on the proximity metric, i.e. access in less than 5 min on foot with an average speed of 4.5 km/h. The location of the agent during the interval corresponds to the longest activity location within the interval under consideration. Based on the agents' location and quiet areas availability, indicators related to the accessibility of green and quiet areas are estimated.

2.4. Analysis indicators

Once an accessibility metric for quiet areas is defined, it is possible to distinguish between agents who have access to quiet areas and agents who do not. Based on this distinction, and given a time interval (t), two variables are defined.

The first variable is the number of agents with access to the quiet areas of a green space ($n(t)$). It is the total count of agents whose primary activity location during the specified time interval is within the service area of the quiet areas of green space. This includes both agents who are directly engaged in activities within the quiet areas and those who are near to them. A similar variation of this variable is the number of agents with access to the green space ($N(t)$).

The second variable is the number of agents with access to the quiet areas of a green space ($n(t)$) divided by the total area of the quiet areas of that same green space ($s(t)$). Expressed in the number of agents per squared meter, for the remainder of this study, this variable will be referred to as "accessibility density" ($d(t)$) of the quiet area, see Eq. (1), which represents the density of people in the quiet area if everyone with access decided to go. This variable is employed to differentiate between small quiet areas in highly-attended urban zones and large quiet areas in low-attended urban zones. A variation of this variable is the number of agents with access to the green space ($N(t)$) divided by the total area of the green space (S), which is designated the accessibility density of the green space ($D(t)$).

$$d(t) = \frac{n(t)}{s(t)} \tag{1}$$

It is important to consider that the analytical variables are utilized to describe the accessibility of an area and to provide a comparison of two accessibility perspectives: the current state of quiet areas, which designate quiet areas based on the current state of transport scenario; and the maximum potential of quiet areas, which considers the all green spaces as quiet areas during the study period. Based on this comparison, two indicators are defined.

The first indicator is the number of agents with access to the current quiet areas of green space ($n(t)$) divided by the number of agents with access to the green space ($N(t)$), defined as the "quiet area access ratio" ($k(t)$), see Eq. (2). This indicator is the percentage of agents with access to a quiet area compared to the number of agents with access to the green space. If the value is 0, it can be inferred that no quiet area is present within the green space, or that the current quiet areas are not accessible. Conversely, if the value is 1, it can be inferred that the entire green space is a quiet area, or that the current quiet areas are accessible for all agents that have access to the green area.

$$k(t) = \frac{n(t)}{N(t)} \tag{2}$$

The second indicator is the ratio between the total area of the current quiet areas ($s(t)$) and the total area of the green space (S), defined as the "quiet area surface ratio" ($e(t)$), see Eq. (3). This indicator is the percentage of the green space that is currently quiet.

$$e(t) = \frac{s(t)}{S} \tag{3}$$

These variables and indicators are estimated for each green space at each 15-minute time interval of the simulation. The temporal average of these values between 12:00 and 14:00 can be used for a global evaluation of accessibility over the study period. In the following, the symbol of the upper bar, e.g. $\bar{n}$, designates the temporal average value of the considered indicators and variables during the study period of the simulation.

2.5. Exemplification case study and data used

In this study, the agent-based framework is implemented in the Lyon Metropolitan Area, which comprises 58 municipalities and had a population of approximately 1.4 million inhabitants in 2020, occupying an area of around 533.7 km^2 (INSEE, 2024).[7]

The objective of this case study is to assess the accessibility of the population to quiet areas during the lunch break period, specifically

[6] Downloaded in June 2024.

[7] insee.fr/fr/statistiques/1405599?geo=EPCI-200046977

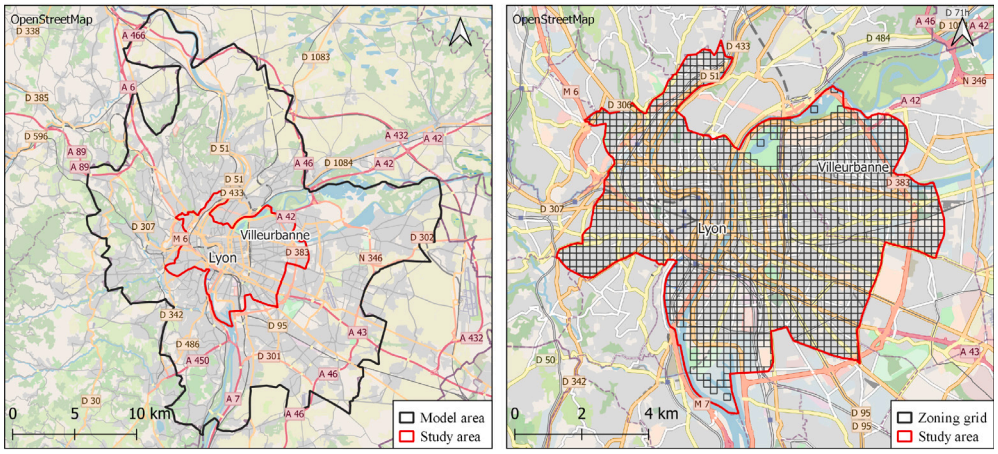


Fig. 2. Model area, study area, and zoning grid of the agent-based framework of Lyon Metropolitan Area.

between the hours of 12:00 and 14:00. The lunch break represents the longest rest period within the workday and may serve as a crucial opportunity for recovery (De Bloom et al., 2017). This period is segmented into 8 time intervals of 15 min. At each time interval, the agents' accessibility to quiet areas is evaluated.

The investigation of quiet area accessibility is approached from two distinct perspectives. Firstly, the current state of accessibility is assessed considering the current simulated noise emissions and population mobility. This current perspective aims to identify quiet and green areas with great accessibility to preserve their acoustic condition. Secondly, the maximum potential scenario is evaluated under the assumption that all green spaces are entirely quiet areas. The mobility of the population, the trajectory of agents, and their locations throughout the simulation are maintained as in the current situation scenario. This potential perspective aims to identify green spaces with the greatest potential for increasing the accessibility to quiet areas, with the further goal of improving their acoustic environment.

The model of this study is a representative mobility scenario of a typical working day in the year 2015, the year of the last household travel survey. The synthetic population is simulated based on a 100% sampling rate. This means that the whole population of the study area is simulated in a large-scale transport model. There are more than 1.4 million agents engaged in the performance of their daily activities.

The simulation is based on the Lyon Metropolitan Area, while the study area is composed of the cities of Lyon and Villeurbanne (62.8 km^2), see Fig. 2. To avoid biases at the simulation boundary, a zone larger than the study area was simulated. This is necessary, for example, to account for acoustic influences from nearby roads that are not integrated into the simulation area.

The location of agents within a specified time interval is associated with a specific point in space. However, to visualize the spatialization of accessibility at the urban scale, a zoning system must be established. In this study, the study area is divided into a zoning grid of 200 × 200 m, see Fig. 2. This grid facilitates the calculation of indicators, such as the number of agents within each cell with access to at least one green zone. This allows for the visualization of the spatial distribution of indicators at the urban scale.

The framework's population and transport input data are openly available and their treatment has been described in detail in previous studies (Hörl & Balac, 2021a, 2021c). The input data for the agent-based transport model are the French population census of 2015 (*Institut national de la statistique et des études économiques*, INSEE), the Population work and education commute data of 2015 (INSEE), the networks and buildings data (OpenStreetMap), the General Transit Feed Specification (GTFS) data of public transport lines from different sources (SNCF TER, Intercités, TGV, etc.), the National address database of 2015 (*Institut national de l'information géographique et forestière*, IGN),

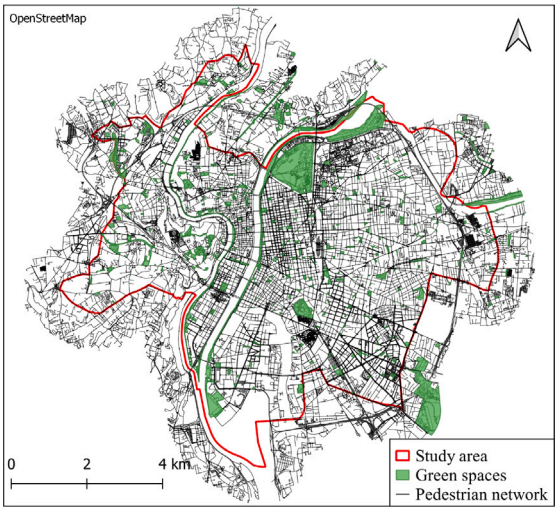


Fig. 3. Green spaces and pedestrian network of the study area of Lyon and Villeurbanne.

the National service and facility database of 2019 (INSEE), the National enterprise census (INSEE), the Lyon Metropolitan Area household travel survey of 2015 (*Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement*, CEREMA), and the household income data of 2015 (INSEE).

This study requires specific data on green spaces in the study area. The Lyon Metropolitan Area[8] openly provides a database called "parks and gardens" with its green spaces open to the public (Métropole, 2024). In this database (GeoJSON format), each green space is provided with its polygon geometry and its attributes, including the identifier, name, street, postal code, city, surface, manager in charge, opening hours, etc. The level of detail about the green space varies, with some spaces having all the data and others having missing data. For example, not all opening times are specified. The data used in this case study are the geometries (multi-polygon, resolution not specified) and the names of the green spaces.

The full name of the green spaces begins with a word indicating the type of space, for example "Parc de la Tête d'Or", which indicates that it is a park. From the name, a new attribute of the space is extracted,

[8] data.grandlyon.com/portail/en/jeux-de-donnees/parcs-jardins-metropole-lyon/info, downloaded in March 2024.

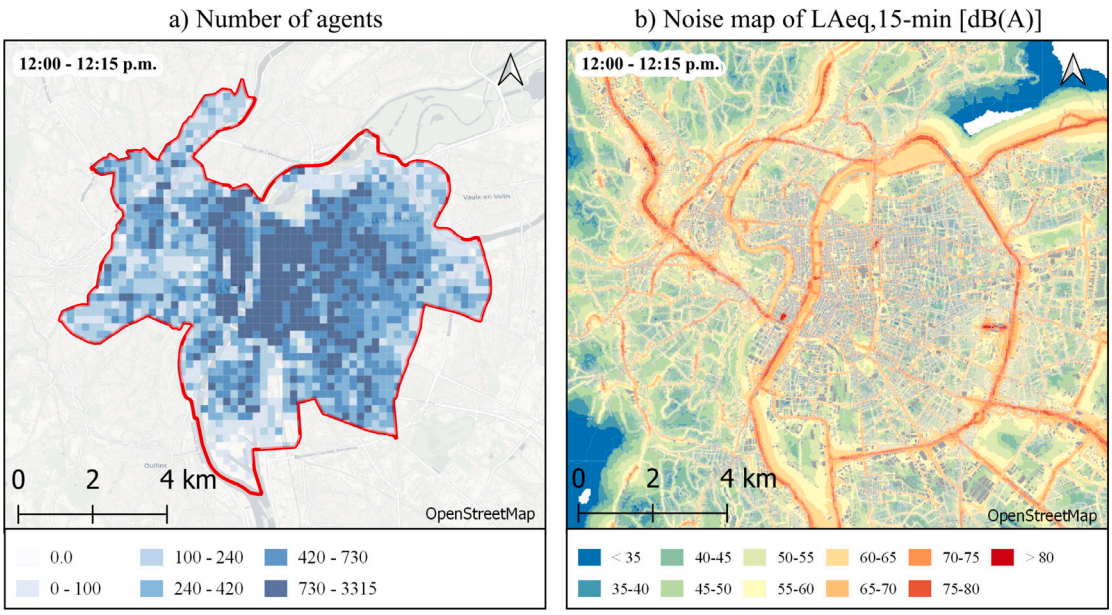


Fig. 4. Maps between 12:00 and 12:15 of the spatial distribution of agents and the noise of road traffic, expressed by the LAeq,15-minutes.

its category: gardens, parks, squares, river banks, woodlands, among others.

The green areas are filtered according to the study area, considering the parks within a margin of 1 kilometer beyond the study area's border, in order to improve consideration of agent access in these regions. The geometries are redefined, excluding the buildings' footprints inside them. No additional indicator related to specific landscape attributes, such as the percentage of green surface, is applied to filter or classify green spaces. The study area contains 371 green spaces eligible to be designated as quiet areas, see Fig. 3. The total surface area of these green spaces is 5.5 km^2.

3. Results

3.1. Overall assessment of quiet areas accessibility

The assessment of accessibility to quiet areas, as estimated and measured by agent-based models, is predicated on two data components: the geographical coordinates of the agents (activity location) and the environmental acoustic conditions, particularly the level of transport-related noise. To illustrate the spatialization of these data resulting from the implementation of the framework at Lyon and Villeurbanne, Fig. 4 shows two maps: the agent spatialization, aggregated in a zoning grid, and the noise map, both between 12:00 and 12:15. These results are situated within a sequence of eight 15-minute intervals between 12:00 and 14:00.

The distribution of noise emissions and agents in space and time determines access opportunities to quiet areas. To visualize and quantify accessibility, Fig. 5 presents the spatial distribution of the temporal average of the number of agents with access to at least a quiet area, as well as the number of agents with access to at least a green space, quiet or not. These maps reveal urban areas that currently lack access to quiet areas, considering current mobility conditions, and areas lacking access to green spaces (see Fig. 5).

In the study area, the mean number of agents between 12:00 and 14:00 is around 661,000 agents. Among these agents, 29.6% have access to at least one current green and quiet space. If all green spaces were to be designated as quiet, 85.3% of agents would have access, which is the maximum value of accessibility if no new green spaces are created.

The potential of existing quiet and green spaces can be analyzed in greater detail by examining the distribution of accessible green or quiet surface area per agent, as illustrated in Fig. 6. In this analysis, all agents in the study area between 12:00 and 12:15 are considered, totaling approximately 825,000 agents. In the case of accessibility to current quiet areas (green line) or green space (red line), for a given value of area surface on the x-axis, the y-axis value represents the percentage of agents who have access to an area surface greater than or equal to that value. As the value of the surface increases, fewer agents meet the condition of having that area access opportunity.

Between investing in the development of new green spaces or acoustically preserving existing ones, these comprehensive results suggest that existing spaces already possess considerable accessibility potential concerning quiet areas and noise restorativeness. Nevertheless, this potential remains underutilized. In addition, the results indicate that the observed gains of existing green spaces are associated not only with access to at least one quiet area but also with the extent of these areas, which may be related to their quality.

3.2. Assessment of current quiet areas

Concerning the accessibility to current quiet areas, Table 2 presents a ranking of 8 green spaces ordered by the highest number of agents with access to the current quiet areas ($\overline{n}$). In addition to the name and category of the green space, the table also shows the temporal average values of quiet surface area ($\overline{s}$), the accessibility density of quiet area ($\overline{d}$), the quiet area access ratio ($\overline{k}$), and the quiet area surface ratio ($\overline{e}$).

The six green spaces with the highest number of agents with access are gardens: Jardin Dalle Rozier, Jardin Saint Michel, Jardin Clos Carret, Jardin de la Grande Côte, Jardin d'Essling, and Jardin Burdeau. They are all situated within the courtyards of highly attended central urban zones. Their boundaries are entirely or almost entirely protected by surrounding buildings.

These green spaces differ in terms of the quiet surface area, with the smallest being the Jardin Burdeau (garden), which has a quiet surface area of 163 m^2 and an accessibility density of quiet area of 33.8 agents/m^2, and the largest being Parc Sergent Blandan (park), which has a quiet surface area of 23,092 m^2 and an accessibility density of quiet area of 0.3 agents/m^2.

Among these green spaces, the number of agents with access to quiet areas is almost fully developed compared to its maximum potential,

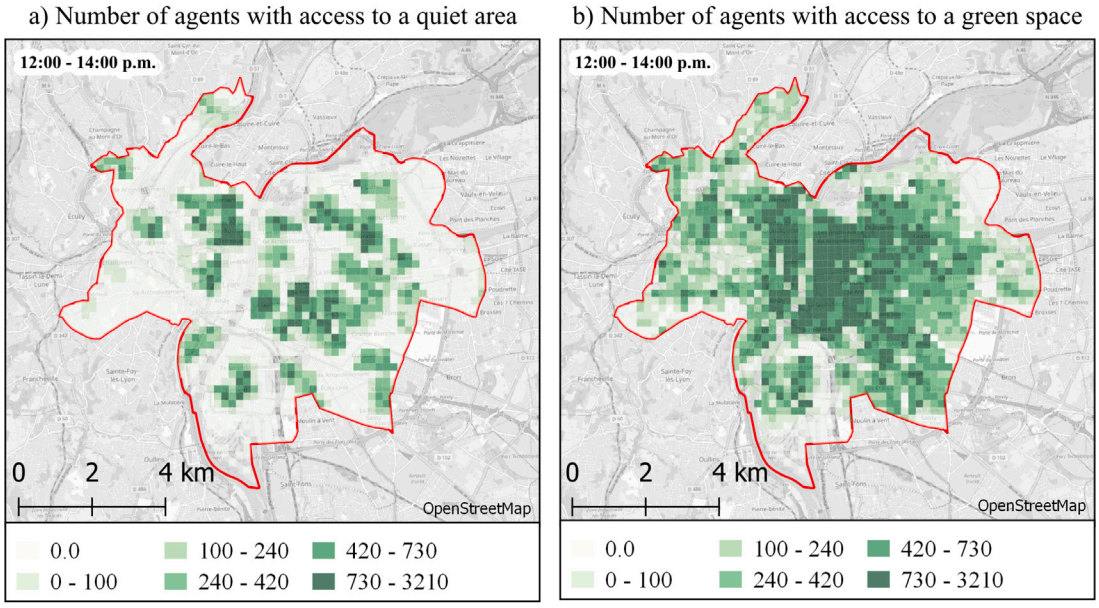


Fig. 5. Maps of the temporal average of the number of agents with access to a quiet area or to a green space between 12:00 and 14:00.

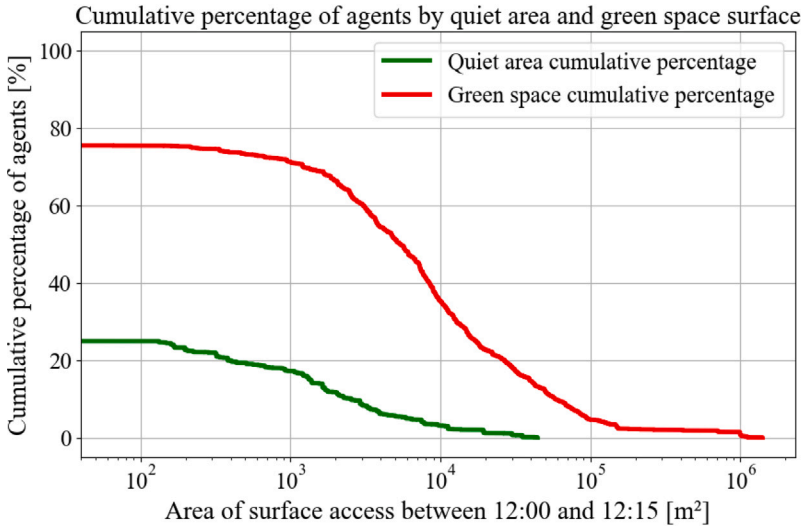


Fig. 6. Distribution of quiet and green surface access per agent. Cumulative percentage of agents whose access to quiet or green areas is greater than or equal to a specific area value.

Table 2
Green spaces ordered by the highest temporal average of the number of agents with access to current quiet areas ($\overline{n}$) between 12:00 and 14:00.

ID	Name	Category	$\overline{n}$ [No.]	$\overline{s}$ [m²]	$\overline{d}$ [No./m²]	$\overline{k}$	$\overline{e}$
69	Jardin Dalle Rozier	Garden	9177	354	26.2	1.0	0.8
153	Jardin Saint Michel	Garden	7941	1637	4.9	1.0	1.0
64	Jardin Clos Carret	Garden	7786	2920	2.7	1.0	0.9
74	Jardin de la Grande Côte	Garden	7145	3870	1.9	0.8	0.4
95	Jardin d'Essling	Garden	6965	320	21.8	1.0	1.0
60	Jardin Burdeau	Garden	6307	163	33.8	0.9	0.9
195	Parc Sergent Blandan	Park	6211	23,092	0.3	0.7	0.2
189	Parc Joseph Kaplan	Park	6163	3610	1.9	1.0	0.7

Temporal averages of the number of agents with access to the quiet area ($\overline{n}$); quiet surface area ($\overline{s}$); accessibility density of quiet area ($\overline{d}$); quiet area access ratio ($\overline{k}$); quiet area surface ratio ($\overline{e}$).

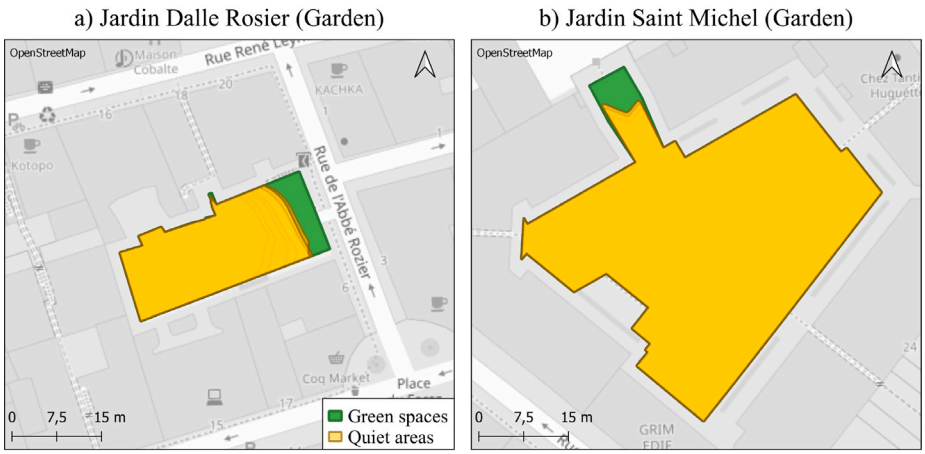


Fig. 7. Green space and quiet area geometries of two green spaces with a high number of agents with access to their current quiet areas, the Jardin Dalle Rosier (ID 69) and Jardin Saint Michel (ID 153).

which corresponds to the total number of agents with access to the entire green space. Six of eight spaces have a quiet area access ratio value greater than 90%. The exceptions are the Jardin de la Grande Côte, with a quiet area access ratio of 80%, and the Parc Sergent Blandan, with a quiet area access ratio of 70%.

With regard to the quiet area surface, four out of eight green spaces have a quiet area surface ratio lower than 90%. Then, increasing the quiet area surface of these spaces could reduce their accessibility density, e.g. Jardin Dalle Rosier, or, in certain cases, increase the average number of agents with access, e.g. Jardin de la Grande Côte and Parc Sergent Blandan.

The values of quiet area access ratio ($\bar{k}$) and quiet area surface ratio ($\bar{e}$) are directly proportional. The larger the quiet area of a green space, the more likely it is to be accessible to more people. However, the size of the green space and the distribution of its quiet areas also influence this proportionality relationship. In green spaces of medium or large size, especially those with limited and spaced-out access points, quiet areas at one extremity become inaccessible to the agents near the other extremity, e.g. Jardin de la Grande Côte. However, for small spaces with only one access point, the quiet area access ratios do not vary much with the increase in their quiet areas surface, e.g. Jardin Dalle Rozier.

Fig. 7 illustrates two green spaces with a high number of agents with access to their current quiet areas. The garden Jardin Dalle Rozier is estimated to have an average number of agents with access of 9,177. This small green space is protected by the surrounding buildings. The garden Jardin Saint Michel is estimated to have an average number of agents with access of 7,941 agents. Similarly, it is accessed via narrow walkways between the buildings, which completely encircle it.

3.3. Assessment of potential quiet areas

The analysis of the potential quiet areas assumes that all green spaces are quiet areas throughout the study period. The objective of the analysis is to identify which green spaces would provide the greatest gain in terms of accessibility to quiet areas.

Table 3 illustrates the ranking of 8 green spaces ordered by the highest average number of agents with access to their perimeter. Among these green spaces, 4 are river banks, i.e. linear parks along rivers, namely the Rives de Saône 2e, the Berges du Rhône 7e, the Rives de Saône 1er, and Berge du Rhône 6e. The temporal average of the number of agents with access to these green spaces are 23,279, 14,764, 12,144, and 11,163 agents, respectively. These river banks are notable for their length and vastness, as well as their permeation of densely attended urban zones. This is historically justified, as the city of Lyon itself was founded and developed from its rivers.

Another category of green spaces with a high potential for accessibility to quiet areas is those that are small spaces situated in high-attended urban zones. The Square Moncey-Dunoir, for instance, is a playground situated in the heart of the Lyon Metropolitan Area. It has an average accessibility of 12,544 agents.

A comparison of these two green space profiles suggests that compact green spaces with small perimeters and high accessibility densities may be easier to acoustically improve than large, sprawling green spaces. Fig. 8 shows the Rives de Saône 2e (river bank), with a perimeter of 9,002 meters and an average accessibility density of 0.4 agents/m^2, and the Square Moncey-Dunoir (square), with a perimeter of 234 m, and an average accessibility density of 8.4 agents/m^2. As the square has a smaller perimeter and less surface area per inhabitant to control, the implementation of traffic restriction measures located in nearby streets, or even the construction of acoustic panels, for example, are viable short-term solutions. The same cannot be stated for the Rives de Saône 2e. However, if the high accessibility density leads to high attendance of the green space, its restorative qualities may be compromised due to overcrowding (Ekkel & de Vries, 2017).

These green spaces demonstrate considerable potential for an increase in the number of agents with access to quiet areas. The access ratio indicates the extent to which this accessibility potential is currently established. In this regard, it is noteworthy that the potential for quiet areas within these green spaces is insufficiently explored. An exception is the Parc de la Tête d'Or (Garden), which currently has a 30% quiet area access ratio and 10% of its surface area designated as quiet.

3.4. Comparison between current and potential quiet areas

To summarize the accessibility to quiet areas from both current and potential perspectives, the green spaces were classified into five categories according to the average number of agents with access to their quiet areas. These five categories are based on the quartiles of the number of agents with access to the green spaces, in addition to the null category, and are described as *none* (no quiet area or accessibility, i.e. the number of agents with access = 0), *very low* (minimum to low quartile, i.e. $0 \leq$ no. of agents $<$ 1800), *low* (low quartile to median, i.e. 1800 $\leq$ no. of agents $<$ 3200), *high* (median to upper quartile, i.e. 3200 $\leq$ no. of agents $<$ 5400), and *very high* (upper quartile to maximum, i.e. 5400 $\leq$ no. of agents $<$ 23300). The mapping of green spaces following this accessibility classification is shown in Fig. 9.

A spatial comparison between the two classifications reveals the green spaces whose current accessibility has already been established or could be established in the future. Furthermore, map (b) illustrates a crown-shaped pattern of access from the most populated city center

Table 3
Green spaces ordered by the highest temporal average of the number of agents with access to potential quiet areas ($\overline{N}$) between 12:00 and 14:00.

ID	Name	Category	$\overline{N}$ [No.]	S [m^2]	$\overline{D}$ [No./m^2]	$\overline{k}$	$\overline{e}$
203	Rives de Saône 2e	River bank	23,279	65,957	0.4	0.1	0.2
48	Berges du Rhône 7e	River bank	14,764	47,689	0.3	0.0	0.0
283	Square Moncey-Dunoir	Square	12,544	1487	8.4	0.0	0.0
202	Rives de Saône 1er	River bank	12,144	12,293	1.0	0.0	0.0
178	Parc de la Téte d'Or	Park	11,709	993,785	0.01	0.3	0.1
332	Square Ste-Marie Perrin	Square	11,530	4627	2.5	0.0	0.0
47	Berge du Rhône 6e	River bank	11,163	32,385	0.3	0.0	0.0
66	Jardin Cdt. Aubertin	Garden	10,404	6094	1.7	0.0	0.0

Temporal averages of the number of agents with access to green area ($\overline{N}$); green space surface area (S); accessibility density of green space ($\overline{D}$); quiet area access ratio ($\overline{k}$); quiet area surface ratio ($\overline{e}$).

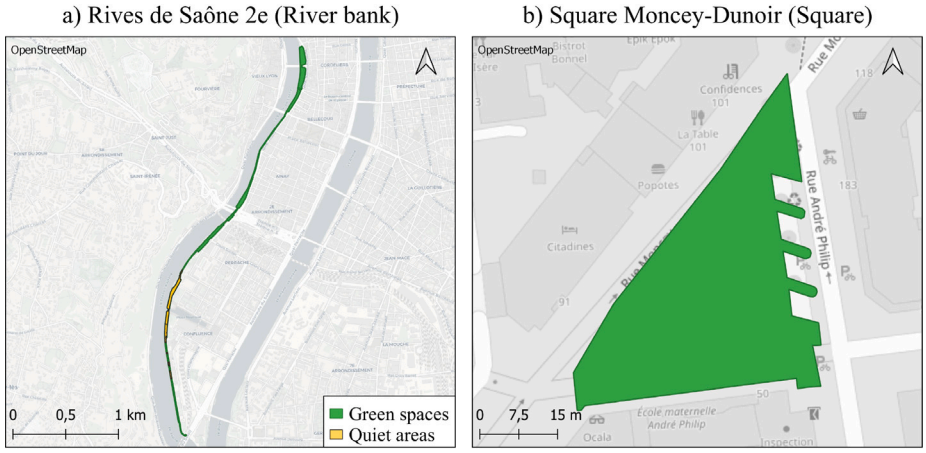


Fig. 8. Green space and quiet area geometries of two green spaces with high potential gain to the number of agents with access to quiet areas, the Rives de Saône 2e (ID 203) and Square Moncey-Dunoir (ID 283).

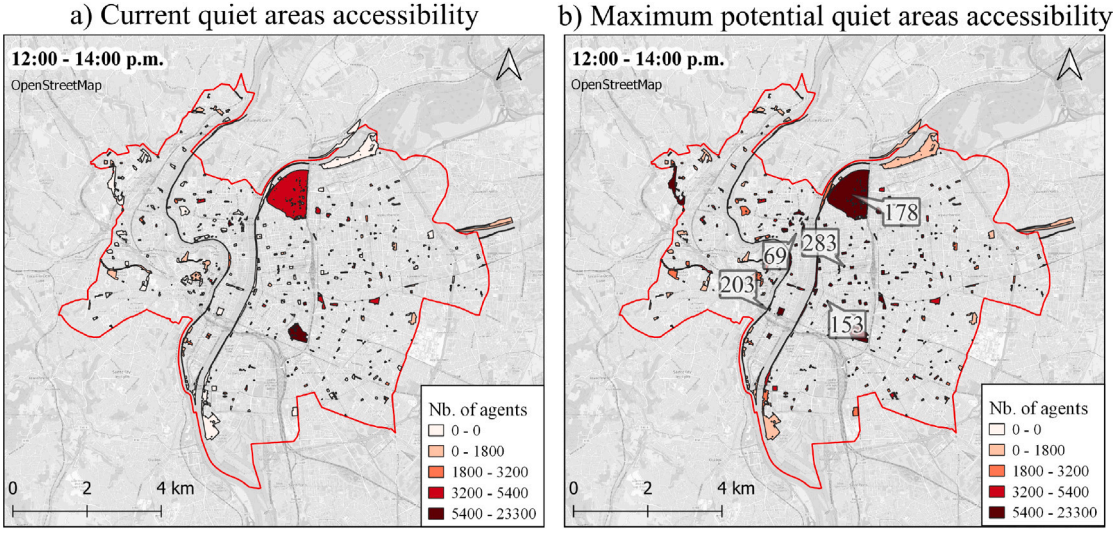


Fig. 9. Quiet area accessibility categories based on the temporal average between 12:00 and 14:00 of the number of agents with access to a quiet area for the current and the maximum potential of the green spaces.

based on the classification of maximum potential quiet areas accessibility (i.e., if all green areas were quiet). This pattern is fragmented by territorial cuts, such as rivers, bridges, and hills, as well as peripheral zones with high attendance, both of which impact accessibility.

A detailed quantitative description can be obtained by comparing the values of current accessibility and maximum potential accessibility for the 371 green spaces eligible to be designated as quiet. Fig. 10 shows the time average of the number of agents with access to the green space and the number of agents with access to its current quiet areas. The vertical distance between the location of the point and the red line represents the potential gain in terms of accessibility to quiet areas. For green spaces situated on the $x = y$ line, such as the Dalle Rosier Garden (ID 69) and the Saint Michel Garden (ID 153), the potential for accessibility to the quiet area is maximum. In contrast, for green spaces on the $y = 0$ line, such as Square Moncey-Dunoir (ID 283), the potential for accessibility to the quiet area remains unexploited. In the intermediate point locations, such as Parc de la Tête d'Or (ID 178) and

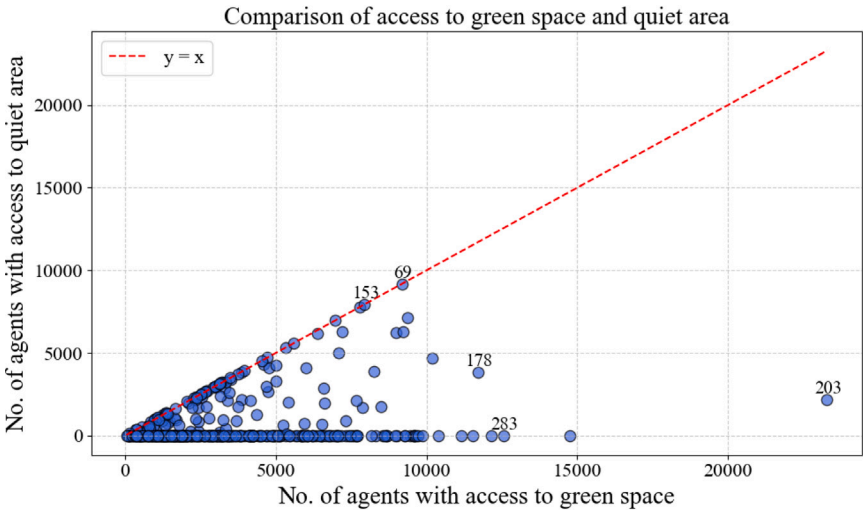


Fig. 10. Comparison of the temporal average of the number of agents with access to green space and its quiet areas.

Rives de Saône 2e (ID 203), the accessibility potential is only partially developed.

4. Discussion

The analysis of the spatial distribution of agents with access to at least one quiet area provides insights into urban zones that are deficient in quiet area accessibility based on existing green spaces. The accessibility assessment takes into account the urban spatialization of activities over time and the physical disruption of territorial access, such as rivers. Understanding the potential of existing spaces and their connectivity to the population is important considering that more green spaces do not necessarily mean higher accessibility (Chen & Chang, 2015). In conjunction, agent-based models provide an assessment of the size of quiet areas accessible to each agent. The size of accessible quiet areas raises questions about the quality of these green spaces and the inequality of environmental opportunities within a population (Anthun et al., 2019; Comber, Brunsdon, & Green, 2008).

Focusing on the current most accessible quiet spaces, two points of vigilance emerge. First, the need to protect these spaces by ensuring that they are not adversely affected by urban transformations. Secondly, the possibility of improving the accessibility of existing quiet spaces. Considering all green spaces, this study identified spaces that may be overlooked by urban planning due to their small size, but which are of great importance in terms of accessibility to quiet areas. This case is exemplified by the importance of public courtyard gardens (Sinou & Perakaki, 2015), which currently serve as noise refuges in densely urbanized areas. When the focus is shifted to the most accessible green spaces, it becomes apparent that certain areas, if accompanied by appropriate acoustic enhancement, can achieve significant gains in terms of accessibility to quiet areas. This case is exemplified by linear green spaces along river banks.

The current analysis is based on a theoretical comparison of current conditions with the maximum potential of quiet areas within existing green spaces. However, scenario-based analyses are necessary to develop concrete planning guidance. These scenarios permit the evaluation of how specific interventions tailored to different urban and acoustic contexts can improve the acoustic properties of open green spaces. For example, the potential of targeted modifications to public green spaces, such as the addition of acoustic infrastructure like earth berms, vegetative buffers, or acoustic screens, to reduce environmental noise levels can be tested (Nilsson, Bengtsson, & Klæboe, 2014; Van Renterghem, Dekoninck, & Botteldooren, 2020; Van Renterghem et al., 2015). Similarly, modifying mobility and traffic behavior through modal shifting to active mobility, reduced speed zones, or vehicle access restrictions near quiet areas can be evaluated for their acoustic effects and influence on accessibility. In this regard, strategies to improve accessibility are also linked to broader land use planning objectives, such as promoting mixed-use facilities, increasing urban density, and reducing the distance between residential areas and daily activity centers (Mavoa et al., 2018; Yurrita et al., 2021). These urban planning strategies may support quieter environments and more equitable access to green spaces. Agent-based models are modular and flexible tools that can simulate the combined effects of such interventions and behavioral changes on urban mobility patterns and acoustic environments, offering insights into spatial and social disparities in accessibility.

Although this study centers on public open green spaces, which are directly influenced by planning decisions and accessible to all, private green areas, such as inner courtyards, gardens, or semi-private communal spaces, could also be introduced in future analyses to extend the scope of acoustic planning (Haaland & van Den Bosch, 2015; Hall, 2010). Despite legal and spatial constraints, these spaces may significantly contribute to noise restoration, particularly in dense urban contexts. Therefore, considering private green space is not only essential to fully understand the spatial distribution of quiet areas, but also to address inequalities in access to green and quiet amenities (Kabisch & Haase, 2014; Lin, Fuller, Bush, Gaston, & Shanahan, 2014). Urban design guidelines and incentives could support the integration of these elements, acknowledging the complementary role of private green infrastructure in a city-wide quiet area strategy. Thus, evolving from a theoretical framework to scenario-based planning also allows for the formulation of actionable strategies that include both public and private dimensions of the urban soundscape.

In light of the constant technological evolution of agent-based models for environmental assessment, it is imperative to address the prevailing limitations and potential avenues for enhancement of the framework. The application of this study encompasses a transport model, an accessibility model, an acoustic model, and a specific definition of quiet areas. Further examination of these components is necessary.

Considering the current agent-based framework, the resolution of the algorithm for assigning activity locations to agents does not enable the analysis of attendance of specific locations. With regard to green spaces, the activity categories in the household-travel survey do not permit clear identification of activities in green spaces or outdoor leisure activities. Furthermore, the modeling of activity locations is conceptually related to the notion of facility, i.e., buildings and houses of the national address database, then outdoor spaces are underrepresented (Luquezi, Aumond, Gastineau, Le Bescond, & Can, 2023; Luquezi et al., 2024a). Complementary data on green space attendance would

be required to model the capacity and attractiveness of these spaces into the assignment algorithms.

The present study focuses on the lunch break as a case study, examining this period because recovery from noise is particularly relevant during that time. However, it is also pertinent to analyze the availability of quiet areas at other times of the day, particularly during peak hours, when noise levels are higher. Including the opening hours of green spaces and analyzing their accessibility at times of greatest demand for leisure activities, such as late afternoon, can provide complementary urban planning insights. The value of dynamic assessment through an agent-based model lies in its ability to investigate environmental opportunities at various times of the day and through diverse analytical perspectives.

The access metric can be multi-modal, incorporating an array of access metrics that vary according to distinct socio-demographic groups. For instance, the mean walking time for accessibility may be contingent on the age of the agent, and further investigation into the environmental opportunities at varying distances would be insightful (Gong, Zheng, & Ng, 2016). The customization of accessibility algorithms in agent-based models enables the formulation of complex accessibility models based on the specific accessibility needs and restrictions of agents or groups of agents.

Continuous enhancements to acoustic models are necessary to capture nuances in environmental physical conditions, e.g. agglomeration relief, tunnels, acoustic screens, and multi-modal sources of noise, including aircraft noise, railway noise, and construction noise. Current acoustic modeling technology enables all of these improvements, which require detailed implementation.

Beyond environmental noise, including sounds that influence acoustic perception should be considered to accurately describe acoustic environments. It is important to consider human-made, e.g., human voice, and natural sounds can play a significant role in the perceptual evaluation of the acoustic environment of green spaces (Jeon & Hong, 2015). Aumond, Jacquesson, and Can (2018) propose a stochastic approach to assess the temporal sound distribution for multiple sound sources that enable the estimation of source-oriented indicators, such as the percentage of the time when a given sound source emerges from environmental sounds. These indicators can enhance the acoustic description of spaces eligible for quiet area designation.

The utilization of noise and size thresholds for the delineation of quiet areas engenders a binary classification of urban spaces, with accessibility results that are sensitive to these parameters (Luquezi, Le Bescond, Aumond, Gastineau, & Can, 2024b). Certain practices for defining quiet areas involve considering the quiet area in its acoustic context, using noise indicators that compare the sound level in the space of interest with its surroundings, while other practices involve a combined assessment of the spatial distribution of sound levels in a space (De La Maza et al., 2019).

Moreover, for a nuanced and comprehensive evaluation of the quality of the acoustic environment, human perception plays a pivotal role (Aletta et al., 2018; Brown et al., 2016). One potential method for the evaluation of human perception is through in-situ surveys (Aletta et al., 2016). In the context of accessibility to quiet areas, these surveys can complement the analysis by focusing on two main aspects: the evaluation of user/visitor perception of the acoustic environment and the evaluation of space usage and attendance. Studies indicate that perceived accessibility affects green space use more than physical accessibility (Terefe & Hou, 2024; Wang, Brown, Liu, & Mateo-Babiano, 2015), and surveys can provide valuable insights on individual, socio-cultural, physical, and transport factors, influencing this relationship. These insights are also valuable for evaluating quiet areas attendance, as overcrowding may reduce the health benefits that contact with nature provides (Ekkel & de Vries, 2017).

It would be beneficial for future research to examine the spatio-temporal relationship between accessibility to quiet areas and population health. Studies in environmental health research, inspired by theories of temporal geography and spatial ecology, advocate the inclusion of mobility and everyday activities in public health research (Chaix et al., 2013; Perchoux, Chaix, Cummins, & Kestens, 2013; Rainham, McDowell, Krewski, & Sawada, 2010). Commonly, the assessment of environmental opportunities is defined by focusing on the residential location of individuals, often using administrative boundaries to outline the opportunity area. However, because individuals have distinct mobility patterns, administrative neighborhood boundaries may not accurately represent the actual environments to which people are exposed. Agent-based frameworks provide a dynamic approach to studying the influence of everyday mobility on the association between health benefits and proximity to green and quiet spaces.

Another area of research for future study would be to consider the protection of quiet areas within the urban agglomeration for biodiversity protection. In Qiu, Lindberg, and Nielsen (2013), evidence on perceptions of recreational and biodiversity values in urban green spaces indicates that recreational preferences are negatively related to high biodiversity values. Therefore, it is possible that an action plan designed to facilitate human access to quiet and green spaces may inadvertently compromise the conservation of these spaces for biodiversity.

5. Conclusion

Based on an agent-based framework, this study examines the current situation and the potential accessibility of quiet areas within existing green spaces in the Lyon and Villeurbanne cities. With the integration of mobility into the analysis of place effects and opportunities, this spatio-temporal method offers new insights into the accessibility of the population during the lunch break period in a typical working day. The initial observation regarding the population's accessibility indicates that, on average, between 12:00 and 14:00, 29.6% of the agents have access to at least one current green and quiet area (LAeq,15 min value lower than 50 dB(A)). Furthermore, if all the green areas were quiet, 85.3% of the agents would have access. This data serves to reinforce the importance of the protection of the existing public, open, and green spaces within the study area.

Five out of the eight current quiet areas with greater accessibility are green spaces located in courtyards. This demonstrates how noise masking by buildings contributes to the existence of quiet areas in highly attended locations. Of the eight green spaces with the greatest potential for increasing accessibility to quiet areas, linear parks alongside rivers are particularly noteworthy. However, small compact parks in highly attended urban zones may be easier to improve acoustically due to their small perimeter and high accessibility density.

Assessment improvements of the method were raised, including the need to include human contextual perception in the assessment of quiet areas. In terms of prospective research, the proposed methodology has the potential to serve as a foundational framework for research initiatives on the understanding of the interplay between dynamic quiet areas accessibility and population health features, as well as the preservation of quiet areas for biodiversity conservation.

In conclusion, the flexibility of agent-based models, with their potential for spatio-temporal analysis of the population's environmental opportunities, is confronted with the challenges of modeling at the scale of the individual.

CRediT authorship contribution statement

Leonardo G. Luquezi: Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Writing – original draft. **Valentin Le Bescond:** Validation, Software, Methodology, Formal analysis. **Pierre Aumond:** Writing – review & editing, Software, Resources. **Pascal Gastineau:** Writing – review & editing, Resources, Investigation. **Arnaud Can:** Project administration, Funding acquisition, Writing – review & editing.

Data availability

Data will be made available on request.

References

Aletta, F., Kang, J., & Axelsson, Ö. (2016). Soundscape descriptors and a conceptual framework for developing predictive soundscape models. *Landscape and Urban Planning*, *149*, 65–74. http://dx.doi.org/10.1016/j.landurbplan.2016.02.001, URL: https://www.sciencedirect.com/science/article/pii/S0169204616000074.

Aletta, F., Oberman, T., & Kang, J. (2018). Associations between positive health-related effects and soundscapes perceptual constructs: A systematic review. *International Journal of Environmental Research and Public Health*, *15*(11), 2392.

Alvarsson, J. J., Wiens, S., & Nilsson, M. E. (2010). Stress recovery during exposure to nature sound and environmental noise. *International Journal of Environmental Research and Public Health*, *7*(3), 1036–1046. http://dx.doi.org/10.3390/ijerph7031036, URL: https://www.mdpi.com/1660-4601/7/3/1036.

Anthun, K. S., Maass, R. E. K., Hope, S., Espnes, G. A., Bell, R., Khan, M., et al. (2019). Addressing inequity: Evaluation of an intervention to improve accessibility and quality of a green space. *International Journal of Environmental Research and Public Health*, *16*(24), 5015.

Aumond, P., Fortin, N., & Can, A. (2020). Overview of the NoiseModelling open-source software version 3 and its applications. In *Inter-noise and noise-con congress and conference proceedings*: *Vol. 261, No. 4*, (pp. 2005–2011).

Aumond, P., Jacquesson, L., & Can, A. (2018). Probabilistic modeling framework for multisource sound mapping. *Applied Acoustics*, *139*, 34–43.

Axhausen, K. W., Horni, A., & Nagel, K. (Eds.), (2016). *The multi-agent transport simulation MATsim*. Ubiquity Press, http://dx.doi.org/10.5334/baw, URL: https://library.oapen.org/handle/20.500.12657/32162.

Barbosa, O., Tratalos, J. A., Armsworth, P. R., Davies, R. G., Fuller, R. A., Johnson, P., et al. (2007). Who benefits from access to green space? A case study from Sheffield, UK. *Landscape and Urban Planning*, *83*(2–3), 187–195.

Bastarianto, F. F., Hancock, T. O., Choudhury, C. F., & Manley, E. (2023). Agent-based models in urban transportation: review, challenges, and opportunities. *European Transport Research Review*, *15*(1), 19. http://dx.doi.org/10.1186/s12544-023-00590-5, URL: https://doi.org/10.1186/s12544-023-00590-5.

Battaner-Moro, J., Barlow, C., & Wright, P. (2010). A quiet area accessibility metric for the Southampton urban agglomeration. In *Proceedings of Internoise 2010*.

Bocher, E., Guillaume, G., Picaut, J., Petit, G., & Fortin, N. (2019). NoiseModelling: An open source GIS based tool to produce environmental noise maps. *ISPRS International Journal of Geo-Information*, *8*(3), 130. http://dx.doi.org/10.3390/ijgi8030130, URL: https://www.mdpi.com/2220-9964/8/3/130.

Boeing, G. (2017). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, *65*, 126–139. http://dx.doi.org/10.1016/j.compenvurbsys.2017.05.004, URL: https://www.sciencedirect.com/science/article/pii/S0198971516303970.

Brocolini, L., Lavandier, C., Quoy, M., & Ribeiro, C. (2013). Measurements of acoustic environments for urban soundscapes: Choice of homogeneous periods, optimization of durations, and selection of indicators. *Journal of the Acoustical Society of America*, *134*(1), 813–821. http://dx.doi.org/10.1121/1.4807809, URL: https://doi.org/10.1121/1.4807809.

Brown, A. L., Gjestland, T., & Dubois, D. (2016). Acoustic environments and soundscapes. *Soundscape and the Built Environment*, 1–16.

Chaix, B., Méline, J., Duncan, S., Jardinier, L., Perchoux, C., Vallée, J., et al. (2013). Neighborhood environments, mobility, and health: towards a new generation of studies in environmental health research. *Revue D'Epidemiologie Et de Sante Publique*, *61*, S139–S145.

Chen, J., & Chang, Z. (2015). Rethinking urban green space accessibility: Evaluating and optimizing public transportation system through social network analysis in megacities. *Landscape and Urban Planning*, *143*, 150–159.

Comber, A., Brunsdon, C., & Green, E. (2008). Using a GIS-based network analysis to determine urban greenspace accessibility for different ethnic and religious groups. *Landscape and Urban Planning*, *86*(1), 103–114.

Cucurachi, S., Schiess, S., Froemelt, A., & Hellweg, S. (2019). Noise footprint from personal land-based mobility. *Journal of Industrial Ecology*, *23*(5), 1028–1038. http://dx.doi.org/10.1111/jiec.12837, URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12837.

De Bloom, J., Sianoja, M., Korpela, K., Tuomisto, M., Lilja, A., Geurts, S., et al. (2017). Effects of park walks and relaxation exercises during lunch breaks on recovery from job stress: Two randomized controlled trials. *Journal of Environmental Psychology*, *51*, 14–30.

De La Maza, M. S., Blanes, N., Ubach, R., Fons, J., & Ramos, M. J. (2019). *Status of quiet areas in European urban agglomerations*: *Technical report*, URL: https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-10-2019-status-of-quiet-areas-in-european-urban-agglomerations.

Ekkel, E. D., & de Vries, S. (2017). Nearby green space and human health: Evaluating accessibility metrics. *Landscape and Urban Planning*, *157*, 214–220. http://dx.doi.org/10.1016/j.landurbplan.2016.06.008, URL: https://www.sciencedirect.com/science/article/pii/S0169204616301153.

European Commission (2002). Directive 2002/49/EC of the European parliament and of the council of 25 june 2002 relating to the assessment and management of environmental noise - declaration by the commission in the conciliation committee on the directive relating to the assessment and management of environmental noise. The European Parliament and the Council of the European Union.

European Commission (2015). Commission directive (EU) 2015/996 of 19 may 2015 establishing common noise assessment methods according to directive 2002/49/EC of the European parliament and of the council. Brussels: The European Parliament and the Council of the European Union.

European Environment Agency (2001). *Towards a local sustainability profile : European common indicators*: *Technical report*, European Commission.

European Environment Agency (2014). In European Environmental Agency (Ed.), *Good practice guide on quiet areas*: *Technical Report 4/2014*, European Environment Agency, URL: https://www.eea.europa.eu/publications/good-practice-guide-on-quiet-areas.

Fenger, J. (1999). Urban air quality. *Atmospheric Environment*, *33*(29), 4877–4900. http://dx.doi.org/10.1016/S1352-2310(99)00290-3, URL: https://www.sciencedirect.com/science/article/pii/S1352231099002903.

Filipan, K., Boes, M., De Coensel, B., Lavandier, C., Delaitre, P., Domitrović, H., et al. (2017). The personal viewpoint on the meaning of tranquility affects the appraisal of the urban park soundscape. *Applied Sciences*, *7*(1), 91.

Gastineau, P., Can, A., Yaméogo, B. F., Luquezi, L. G., Hankach, P., Vandanjon, P.-O., et al. (2023). Modeling exposure to mobility-related pollution: Review and key challenges. *Transportation Research Record*, Article 03611981231208907. http://dx.doi.org/10.1177/03611981231208907, URL: https://doi.org/10.1177/03611981231208907.

Gidlöf-Gunnarsson, A., & Öhrström, E. (2007). Noise and well-being in urban residential environments: The potential role of perceived availability to nearby green areas. *Landscape and Urban Planning*, *83*(2), 115–126. http://dx.doi.org/10.1016/j.landurbplan.2007.03.003, URL: https://www.sciencedirect.com/science/article/pii/S0169204607000722.

Gong, F., Zheng, Z.-C., & Ng, E. (2016). Modeling elderly accessibility to urban green space in high density cities: A case study of Hong Kong. *Procedia Environmental Sciences*, *36*, 90–97.

Gurram, S., Stuart, A. L., & Pinjari, A. R. (2019). Agent-based modeling to estimate exposures to urban air pollution from transportation: Exposure disparities and impacts of high-resolution data. *Computers, Environment and Urban Systems*, *75*, 22–34. http://dx.doi.org/10.1016/j.compenvurbsys.2019.01.002, URL: https://www.sciencedirect.com/science/article/pii/S019897151830156X.

Haaland, C., & van Den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening*, *14*(4), 760–771.

Hall, T. (2010). Goodbye to the backyard?—the minimisation of private open space in the Australian outer-suburban estate. *Urban Policy and Research*, *28*(4), 411–433.

Hankach, P., Le Bescond, V., Gastineau, P., Vandanjon, P.-O., Can, A., & Aumond, P. (2024). Individual-level activity-based modeling and indicators for assessing construction sites noise exposure in urban areas. *Sustainable Cities and Society*, *101*, Article 105188. http://dx.doi.org/10.1016/j.scs.2024.105188, URL: https://www.sciencedirect.com/science/article/pii/S2210670724000180.

Hörl, S., & Axhausen, K. W. (2023). Relaxation–discretization algorithm for spatially constrained secondary location assignment. *Transportmetrica A: Transport Science*, *19*(2), Article 1982068.

Hörl, S., & Balac, M. (2021a). Introducing the eqasim pipeline: From raw data to agent-based transport simulation. *Procedia Computer Science*, *184*, 712–719. http://dx.doi.org/10.1016/j.procs.2021.03.089, URL: https://www.sciencedirect.com/science/article/pii/S1877050921007274.

Hörl, S., & Balac, M. (2021b). Open synthetic travel demand for Paris and île-de-France: Inputs and output data. *Data in Brief*, *39*, Article 107622. http://dx.doi.org/10.1016/j.dib.2021.107622, URL: https://www.sciencedirect.com/science/article/pii/S2352340921008970.

Hörl, S., & Balac, M. (2021c). Synthetic population and travel demand for Paris and île-de-France based on open and publicly available data. *Transportation Research Part C: Emerging Technologies*, *130*, Article 103291. http://dx.doi.org/10.1016/j.trc.2021.103291, URL: https://www.sciencedirect.com/science/article/pii/S0968090X21003016.

Houot, H., Antoni, J.-P., Pujol, S., Lamiral, M., & Mauny, F. (2015). Les mobilités urbaines et leur impact sur l'exposition au bruit : simulation de scénarios prospectifs appliqués à la ville de Besançon. *Transports Urbains*, *126*(1), 16–20. http://dx.doi.org/10.3917/turb.126.0016, URL: https://www.cairn.info/revue-transports-urbains-2015-1-page-16.htm.

INSEE (2024). Intercommunalité-Métropole de métropole de Lyon. URL: https://www.insee.fr/fr/statistiques/1405599?geo=EPCI-200046977.

Irvine, K. N., Warber, S. L., Devine-Wright, P., & Gaston, K. J. (2013). Understanding urban green space as a health resource: A qualitative comparison of visit motivation and derived effects among park users in Sheffield, UK. *International Journal of Environmental Research and Public Health*, *10*(1), 417–442. http://dx.doi.org/10.3390/ijerph10010417, URL: https://www.mdpi.com/1660-4601/10/1/417.

Jackson, L. E. (2003). The relationship of urban design to human health and condition. *Landscape and Urban Planning*, *64*(4), 191–200.

James, P., Tzoulas, K., Adams, M. D., Barber, A., Box, J., Breuste, J., et al. (2009). Towards an integrated understanding of green space in the European built environment. *Urban Forestry & Urban Greening*, *8*(2), 65–75.

Jeon, J. Y., & Hong, J. Y. (2015). Classification of urban park soundscapes through perceptions of the acoustical environments. *Landscape and Urban Planning*, *141*, 100–111.

Kabisch, N., & Haase, D. (2014). Green justice or just green? Provision of urban green spaces in Berlin, Germany. *Landscape and Urban Planning*, *122*, 129–139.

Kaddoura, I., Kröger, L., & Nagel, K. (2017). An activity-based and dynamic approach to calculate road traffic noise damages. *Transportation Research Part D: Transport and Environment*, *54*, 335–347. http://dx.doi.org/10.1016/j.trd.2017.06.005, URL: https://www.sciencedirect.com/science/article/pii/S1361920917304686.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169–182. http://dx.doi.org/10.1016/0272-4944(95)90001-2, URL: https://www.sciencedirect.com/science/article/pii/0272494495900012.

Lanza, G., Pucci, P., & Carboni, L. (2023). Measuring accessibility by proximity for an inclusive city. *Cities*, *143*, Article 104581.

Le Bescond, V., Can, A., Aumond, P., & Gastineau, P. (2021). Open-source modeling chain for the dynamic assessment of road traffic noise exposure. *Transportation Research Part D: Transport and Environment*, *94*, Article 102793. http://dx.doi.org/10.1016/j.trd.2021.102793, URL: https://www.sciencedirect.com/science/article/pii/S1361920921000973.

Lin, B. B., Fuller, R. A., Bush, R., Gaston, K. J., & Shanahan, D. F. (2014). Opportunity or orientation? Who uses urban parks and why. *PLoS One*, *9*(1), Article e87422.

Luquezi, L. G., Aumond, P., Gastineau, P., Le Bescond, V., & Can, A. (2023). Multi-agents traffic systems and mobility validity range for assessing noise pollution exposure. In *Proceedings of forum acusticum 2023*. Torino.

Luquezi, L. G., Le Bescond, V., Aumond, P., Gastineau, P., & Can, A. (2024a). Current limitations and opportunities for improvements of agent-based transport models for noise exposure assessment. *Journal of Environmental Management*, *368*, Article 122129. http://dx.doi.org/10.1016/j.jenvman.2024.122129, URL: https://www.sciencedirect.com/science/article/pii/S0301479724021157.

Luquezi, L. G., Le Bescond, V., Aumond, P., Gastineau, P., & Can, A. (2024b). Spatio-temporal mapping of urban noise exposure: insights from the agent-based transport model of the Nantes metropolitan area. In *Inter-noise and noise-con congress and conference proceedings*: *Vol. 270, No. 11*, (pp. 161–169).

Luquezi, L. G., Le Bescond, V., Aumond, P., Gastineau, P., & Can, A. (2025). Including everyday mobility with agent-based models in the assessment of critical areas of noise exposure. *Sustainable Cities and Society*, 106551.

Martinuzzi, C., & Lahoud, C. (2020). *Public Space Site-Specific Assessment: Guidelines to Achieve Quality Public Spaces at Neighbourhood Level*: *Technical report*, (p. 88). United Nations Human Settlements Programme, URL: https://unhabitat.org/public-space-site-specific-assessment-guidelines-to-achieve-quality-public-spaces-at-neighbourhood.

Mavoa, S., Boulangé, C., Eagleson, S., Stewart, J., Badland, H. M., Giles-Corti, B., et al. (2018). Identifying appropriate land-use mix measures for use in a national walkability index. *Journal of Transport and Land Use*, *11*(1), 681–700.

Métropole, d. (2024). Parcs et Jardins de la Métropole de Lyon. URL: https://data.grandlyon.com/portail/en/jeux-de-donnees/parcs-jardins-metropole-lyon/info.

Nilsson, M., Bengtsson, J., & Klæboe, R. (2014). *Environmental methods for transport noise reduction*. CRC Press.

Nygren, J., Le Bescond, V., Can, A., Aumond, P., Gastineau, P., Boij, S., et al. (2024). Agent-specific, activity-based noise impact assessment using noise exposure cost. *Sustainable Cities and Society*, *103*, Article 105278. http://dx.doi.org/10.1016/j.scs.2024.105278, URL: https://www.sciencedirect.com/science/article/pii/S2210670724001069.

Payne, S. R., & Bruce, N. (2019). Exploring the relationship between urban quiet areas and perceived restorative benefits. *International Journal of Environmental Research and Public Health*, *16*(9), 1611. http://dx.doi.org/10.3390/ijerph16091611, URL: https://www.mdpi.com/1660-4601/16/9/1611.

Perchoux, C., Chaix, B., Cummins, S., & Kestens, Y. (2013). Conceptualization and measurement of environmental exposure in epidemiology: accounting for activity space related to daily mobility. *Health & Place*, *21*, 86–93.

Peris, E. (2020). *Environmental noise in Europe*: *Publication 22/2019*, European Environment Agency, URL: https://www.eea.europa.eu/publications/environmental-noise-in-europe.

Qiu, L., Lindberg, S., & Nielsen, A. B. (2013). Is biodiversity attractive?—On-site perception of recreational and biodiversity values in urban green space. *Landscape and Urban Planning*, *119*, 136–146.

Rainham, D., McDowell, I., Krewski, D., & Sawada, M. (2010). Conceptualizing the healthscape: contributions of time geography, location technologies and spatial ecology to place and health research. *Social Science & Medicine*, *70*(5), 668–676.

Rey-Gozalo, G., Barrigón Morillas, J. M., Montes González, D., & Atanasio Moraga, P. (2018). Relationships among satisfaction, noise perception, and use of urban green spaces. *Science of the Total Environment*, *624*, 438–450. http://dx.doi.org/10.1016/j.scitotenv.2017.12.148, URL: https://www.sciencedirect.com/science/article/pii/S004896971733574X.

Rey-Gozalo, G., Barrigón Morillas, J. M., Montes González, D., & Vílchez-Gómez, R. (2023). Influence of green areas on the urban sound environment. *Current Pollution Reports*, *9*(4), 746–759. http://dx.doi.org/10.1007/s40726-023-00284-5, URL: https://doi.org/10.1007/s40726-023-00284-5.

Shepherd, D., Welch, D., Dirks, K. N., & McBride, D. (2013). Do quiet areas afford greater health-related quality of life than noisy areas? *International Journal of Environmental Research and Public Health*, *10*(4), 1284–1303. http://dx.doi.org/10.3390/ijerph10041284, URL: https://www.mdpi.com/1660-4601/10/4/1284.

Sinou, M., & Perakaki, R. (2015). Urban courtyard regeneration: offering new public space, environmental diversity and healthy environments during an economic crisis. In *Proceedings of the 2th international conference on "Changing cities"* (pp. 22–26). Porto Heli, Greece.

Sonnenschein, T., Scheider, S., de Wit, G. A., Tonne, C. C., & Vermeulen, R. (2022). Agent-based modeling of urban exposome interventions: prospects, model architectures, and methodological challenges. *Exposome*, *2*(1), osac009. http://dx.doi.org/10.1093/exposome/osac009, URL: https://doi.org/10.1093/exposome/osac009.

Stansfeld, S. A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., et al. (2005). Aircraft and road traffic noise and children's cognition and health: a cross-national study. *The Lancet*, *365*(9475), 1942–1949.

Takano, T., Nakamura, K., & Watanabe, M. (2002). Urban residential environments and senior citizens' longevity in megacity areas: the importance of walkable green spaces. *Journal of Epidemiology & Community Health*, *56*(12), 913–918.

Terefe, A. E., & Hou, Y. (2024). Determinants influencing the accessibility and use of urban green spaces: A review of empirical evidence. *City and Environment Interactions*, Article 100159.

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, *11*(3), 201–230. http://dx.doi.org/10.1016/S0272-4944(05)80184-7, URL: https://www.sciencedirect.com/science/article/pii/S0272494405801847.

Vale, D. S., Saraiva, M., & Pereira, M. (2016). Active accessibility: A review of operational measures of walking and cycling accessibility. *Journal of Transport and Land Use*, *9*(1), 209–235.

Vallée, J. (2017). The daycourse of place. *Social Science & Medicine*, *194*, 177–181. http://dx.doi.org/10.1016/j.socscimed.2017.09.033, URL: https://www.sciencedirect.com/science/article/pii/S0277953617305671.

Van Renterghem, T. (2019). Towards explaining the positive effect of vegetation on the perception of environmental noise. *Urban Forestry & Urban Greening*, *40*, 133–144. http://dx.doi.org/10.1016/j.ufug.2018.03.007, URL: https://www.sciencedirect.com/science/article/pii/S1618866717306696.

Van Renterghem, T., Dekoninck, L., & Botteldooren, D. (2020). Multi-stage sound planning methodology for urban redevelopment. *Sustainable Cities and Society*, *62*, Article 102362.

Van Renterghem, T., Forssén, J., Attenborough, K., Jean, P., Defrance, J., Hornikx, M., et al. (2015). Using natural means to reduce surface transport noise during propagation outdoors. *Applied Acoustics*, *92*, 86–101.

Wang, D., Brown, G., Liu, Y., & Mateo-Babiano, I. (2015). A comparison of perceived and geographic access to predict urban park use. *Cities*, *42*, 85–96.

World Health Organization (2011). *Burden of disease from environmental noise: quantification of healthy life years lost in Europe*. World Health Organization. Regional Office for Europe, URL: https://apps.who.int/iris/handle/10665/326424.

Yurrita, M., Grignard, A., Alonso, L., Zhang, Y., Jara-Figueroa, C. I., Elkatsha, M., et al. (2021). Dynamic urban planning: an agent-based model coupling mobility mode and housing choice. Use case Kendall square. In *Intelligent computing: proceedings of the 2021 computing conference*: *Vol. 2*, (pp. 940–951). Springer.