



# Residential green is associated with reduced annoyance to road traffic and railway noise but increased annoyance to aircraft noise exposure



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## ABSTRACT

**Background:** In recent years, residential green and availability of neighbourhood green spaces came into focus as a potential means to reduce transportation noise annoyance. Literature suggests that various characteristics of residential green may play a role, namely, greenness of the residential areas as quantified by the normalized difference vegetation index (NDVI), visible vegetation from home, and the presence of public green spaces as identified by land use classification data (LU-green), as well as their accessibility and noise pollution (i.e., transportation noise exposure within green areas, how loud/quiet they are). So far, studies mostly focused on road traffic noise in urban areas.

**Objective:** We investigated the effects of residential green on noise annoyance, accounting for different transportation noise sources as well as for the degree of urbanisation.

**Methods:** We complemented the data set of the recent Swiss SiRENE survey on road traffic, railway and aircraft noise annoyance with a wide range of “green” metrics, and investigated their association with annoyance by means of logistic regression analysis (generalized estimating equations).

**Results:** Increasing residential green was found to be associated with reduced road traffic and railway noise annoyance, but increased aircraft noise annoyance. The overall effect corresponded to equivalent level reductions of about 6 dB for road traffic and 3 dB for railway noise, but to an increase of about 10 dB for aircraft noise, when residential green increased from “not much green” (5th percentile of the study sample distribution) to “a lot of green” (95th percentile). Overall, NDVI and LU-green were particularly strongly linked to annoyance. The effects of visible vegetation from home and accessibility and/or quietness of green spaces were, overall, less strong, but depended on the degree of urbanisation. For road traffic noise, visible vegetation and accessibility of green spaces seem to particularly strongly reduce annoyance in cities, while quiet green spaces are more effective in rural areas.

**Conclusions:** Our study emphasizes that residential green should be fostered by city planners, particularly in densely populated areas.

## 1. Introduction

Urban areas are steadily growing in size and population. While in 1955 less than 55% of Europe’s population lived in urban regions, this increased to more than 74% in 2019 (Worldometer, 2020). Growth of urban areas goes along with an increase in noise pollution, particularly transportation noise. Accordingly, around 139 million Europeans were estimated to be exposed to transportation noise exposure in terms of day-evening-night-level ( $L_{den}$ ) exceeding 55 dB in 2017, of whom more

than two thirds live in urban areas (EEA, 2020). Increased noise exposure may have various negative health effects ranging from annoyance (one of the most prevalent noise effects) to sleep disturbance to cardiovascular diseases (WHO, 2011, 2018). Given that noise-induced health effects are likely to increase in future, the question arises whether such negative impacts may be alleviated by promoting possible recovery from noise, e.g., through residential green (parks, gardens, forests etc.) in close vicinity of noise-polluted areas. There is strong evidence from the literature that residential green, i.e., the greenness of

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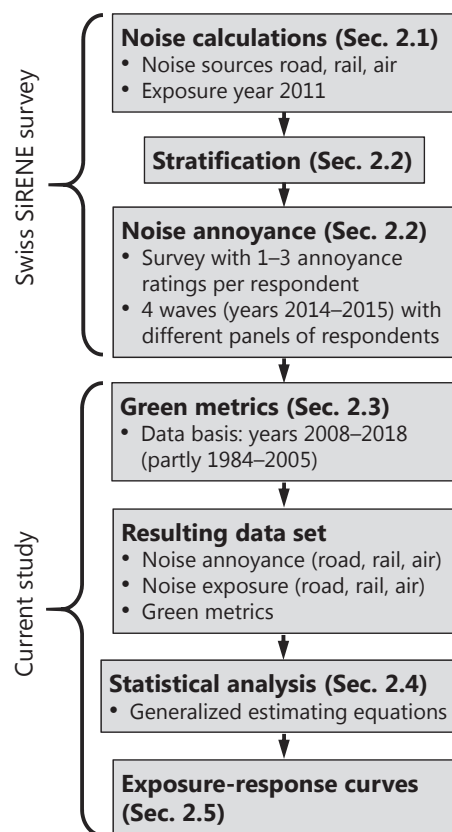
one's living environment, may reduce noise-induced psychological and physiological stress (Chang et al., 2008) and thus a wide range of negative health impacts, such as noise annoyance (Van Renterghem, 2019), hypertension (Dzhambov et al., 2018a), or even mortality (Orioli et al., 2019; Vienneau et al., 2017). These beneficial effects are fostered by so called building capacities (promoting physical activity and social cohesion) as well as restoration (Markevych et al., 2017). The latter is further explained with the stress reduction theory (SRT) by Ulrich (1983) and the attention restoration theory (ART) by Kaplan and Kaplan (1989), as concisely outlined, e.g., by Van Renterghem (2019). The effects of green spaces are thus beneficial in their own right, i.e., they should persist beyond merely reducing noise exposure. The association between residential green and noise annoyance is the focus of the present study.

The association between potentially beneficial environmental exposures and noise annoyance or other health effects can be quantified by means of various metrics for residential green and/or blue, i.e., water bodies. These metrics are generally called “green metrics” in the following account. The satellite-derived normalized difference vegetation index (NDVI) quantifies greenness (Weier and Herring, 2000). Dzhambov et al. (2018b) found increasing NDVI to be associated with decreasing noise annoyance in an urban setting. Further, using detailed land use classification mapping allows identifying designated public parks and green spaces (LU-green) (e.g., Vienneau et al., 2017) and also natural outdoor environments (LU-natural), which comprise green and blue spaces (Gascon et al., 2016, 2017). The potential of LU-green to reduce annoyance seems pronounced (Gidlöf-Gunnarsson and Öhrström, 2007). Finally, the view from home on outdoor vegetation (and/or water bodies), assessed with a Geographic Information System (GIS) based viewshed-analysis (Nutsford et al., 2015) or as self-reported view, was found to reduce annoyance (Leung et al., 2017; Li et al., 2010; Van Renterghem and Botteldooren, 2016).

Not only the quantity (“how much residential green”), but also the quality of green spaces may promote positive health outcomes (van Dillen et al., 2012). First, the size of green spaces may play a role (Rey Gozalo et al., 2019). Second, green spaces should comply with certain design criteria (Pleasant et al., 2013). Li et al. (2010), for example, found that wetland and garden parks in Hong Kong reduced annoyance more effectively than grassy hills. Third, green spaces should be well accessible (Gidlöf-Gunnarsson and Öhrström, 2007). Accordingly, Dzhambov and Dimitrova (2015) found a positive correlation of Euclidean distance with noise annoyance: the closer the less annoyed. Finally, the soundscape of green spaces may be important, in particular with regard to natural (birds, water, vegetation noise) vs. technical (transportation, ventilation) sounds (Alvarsson et al., 2010). Natural sounds are particularly beneficial (Alvarsson et al., 2010; Van Renterghem, 2019). Technical (transportation) noise pollution, in contrast, may be detrimental for stress recovery (Alvarsson et al., 2010).

To date, available studies on the effects of residential green mostly focussed on annoyance to road traffic noise, as noted in recent reviews by Dzhambov (2017) and Van Renterghem (2019). Also, the studies were mainly conducted in urban settings, although the perception of audio-visual settings may differ between urban and rural areas (Brambilla and Maffei, 2006). Further, the studies were based on geographically limited areas. Studies on whether and how (transportation) noise pollution in green spaces modifies the effect of green on annoyance are particularly limited, although noise may affect visitors' satisfaction (Rey Gozalo et al., 2019).

The objective of the present study was to investigate residential green as a modifier for annoyance to different transportation noise sources on a national scale, for Switzerland. Our hypotheses were that (i) increasing residential green is associated with decreasing transportation noise annoyance, (ii) the accessibility of green spaces, their total transportation noise pollution or a combination of both modify this association, and (iii) the degree of urbanization further modifies the



**Fig. 1.** Study design: Noise exposure calculations, stratification and noise annoyance data as taken from the SiRENE survey (Brink et al., 2019a), and green metrics assessment, resulting data set, statistical analysis and resulting exposure–response curves. Details are given in Sections 2.1–2.5 as indicated in the diagram.

effects of residential green. To test these hypotheses, we complemented the data set of the recent Swiss SiRENE survey on road traffic, railway and aircraft noise annoyance (Brink et al., 2019a) with a wide range of “green metrics”, representing (i) residential greenness, (ii) visible vegetation from home, (iii) green and/or natural spaces as well as (iv) their accessibility and (v) noise pollution, and (vi) landscape suitability for nearby recreation. By means of logistic regression analysis, we then established exposure–response curves (ERCs) to quantify the associations of the transportation noise source, residential green and degree of urbanization with noise annoyance.

## 2. Materials and methods

Fig. 1 gives an overview of the methodology, data bases and underlying years as used in the current study. As indicated, details are given in the subsequent Sections 2.1 (noise exposure calculations), 2.2 (stratification and noise annoyance survey), 2.3 (green metrics assessment), 2.4 (statistical analysis) and 2.5 (resulting ERCs).

### 2.1. Noise exposure assessment

The calculated noise exposure data used for the current study were taken from a recent survey which was conducted as part of the interdisciplinary SiRENE project (Brink et al., 2019a). The exposure calculations were carried out Swiss-wide for the year 2011, separately for road traffic, railway and aircraft noise, for each individual dwelling and floor, as described in detail by Karipidis et al. (2014). In short, the calculations were done with the programs (i) sonROAD (emission) (Heutschi, 2004) and StL-86 (propagation) (FOEN, 1987) for road

**Table 1**

Value range of the 22 green metrics (5 main green metrics NDVI, LU-green, LU-natural, visible vegetation from home and landscape suitability for nearby recreation, and their quiet and/or accessible derivatives) of the study sample: 5th, 50th and 95th percentiles. All values represent the 500 m buffer. Blank spaces indicate that no metric was determined.

Green metric	Percentile	NDVI [-]	LU-green [m <sup>2</sup> /m <sup>2</sup> ]	LU-natural [m <sup>2</sup> /m <sup>2</sup> ]	Visible vegetation from home [%]	Landscape suitability for nearby recreation [-]
All spaces	5th	0.33	< 0.01	0.01	0	1.00
	50th	0.55	0.22	0.26	0.19	3.00
	95th	0.72	0.78	0.80	8.45	8.20
Quiet spaces ( $L_{r_{total}} < x$ dB)	< 50 dB	5th	0	0	0	
		50th	0.17	0.02	0.03	
		95th	0.55	0.56	0.58	
	< 45 dB	5th	0	0	0	
		50th	0.04	< 0.001	< 0.01	
		95th	0.43	0.41	0.43	
	< 40 dB	5th	0	0	0	
		50th	< 0.01	0	0	
		95th	0.24	0.23	0.25	
	Accessible spaces	5th		< 0.001	< 0.001	
		50th		< 0.001	< 0.001	
		95th		0.56	0.57	
Quiet ( $L_{r_{total}} < x$ dB) and accessible spaces	< 50 dB	5th	0	0		
		50th	< 0.001	< 0.001		
		95th	0.32	0.33		
	< 45 dB	5th	0	0		
		50th	< 0.001	< 0.001		
		95th	0.19	0.19		
	< 40 dB	5th	0	0		
		50th	0	0		
		95th	0.05	0.05		

traffic noise, (ii) sonRAIL (emission) (Wunderli, 2012) and SEMIBEL (propagation) (FOEN, 1990) for railway noise, and (iii) FLULA2 (Empa, 2010) for aircraft noise, respectively. The calculations account for sound source data (noise emission models) and sound propagation from the individual noise sources (roads, railway lines, individual aircraft flights as obtained from radar data) to the residents' individual dwellings. Propagation calculation includes geometrical divergence, atmospheric absorption, ground effect under the assumption of porous ground, screening by obstacles, and reflection from surfaces (road and rail only) along the individual sound propagation paths, considering terrain and buildings (the latter only for road and rail). Finally, yearly noise exposures ( $L_{den}$ ) were obtained by accounting for the total amount of road, railway and air traffic per time bin. As in Brink et al. (2019a), we used the  $L_{den}$  with the time bins of 07–19 h for day, 19–23 h for evening and 23–07 h for night of the façade point of the respondents' dwellings with the highest exposure to the respective noise source. The calculations yielded individual  $L_{den}$  for road traffic, railway and aircraft noise for each dwelling and floor. Resulting  $L_{den}$  of the respondents ranged from 30 to 82 dB for road traffic and railway noise, and 30–76 dB for aircraft noise (see supplemental material, Section S1).

## 2.2. Noise annoyance data

The annoyance data used for the current study stem from the SiRENE survey (Brink et al., 2019a). In this nation-wide survey, a stratified random sample of the Swiss population was drawn based on exposure strata for road traffic, railway and aircraft noise. For details refer to Brink et al. (2019a).

The survey was conducted in four waves in the years 2014 and 2015, with bulk mailing dates of 18 November 2014, 11 February 2015, 08 May 2015 and 17 August 2015, to control for seasonal effects (Brink et al., 2016). It achieved a response rate of 31%. Each of the four waves interviewed a different panel of respondents, i.e., the respondents were interviewed only once. The questionnaire covered a wide range of topics such as noise sensitivity, dwelling situation, time use, sleeping habits, health and health behaviour, and personality. As a key element,

noise annoyance was assessed with the 5-point verbal and the 11-point numerical ICBEN scales (Fields et al., 2001). For the 11-point scale, the following question was asked in German, Italian or French: “Thinking about the last twelve months, at your home, what number from 0 to 10 best shows how much you were bothered, disturbed, or annoyed by noise from the road, from railways, or aircraft?” In accordance with Brink et al. (2019a), the present study uses the binary variable “highly annoyed (HA)” derived from the 11-point numerical scale. HA is defined as 1 (“highly annoyed”) for annoyance ratings 8, 9 or 10 (top 27% of the 11-point scale), and else as 0 (ratings of 0–7). The binary variable HA was studied instead of the continuous variable annoyance (ratings 0–10) for comparability with field surveys commonly relying on HA, and because HA is usually used for policy purposes (Schultz, 1978; WHO, 2018). Both measures, however, should yield comparable results, as shown, e.g., in a laboratory study by Schäffer et al. (2016).

In total, 5,592 respondents geographically spread across the country participated in the survey. Individuals with no calculated exposure or exposure below 30 dB  $L_{den}$  for the primary noise source were excluded from the analysis. Accordingly, for each respondent, one, two, or three annoyance ratings were reported and included in the analysis, depending on the number of transportation noise sources with  $L_{den} \geq 30$  dB they were simultaneously exposed to. This resulted in a total of 12,064 observations, namely, 5431 (road traffic), 3536 (railway) and 3097 (aircraft), with a hierarchy of levels, the upper level being the respondents and the lower level the 1–3 annoyance ratings per respondents.

The data covers all of Switzerland. Further, it represents all “degrees of urbanization (high to low; urban [cities], peri-urban [towns and suburbs], rural areas)” according to Eurostat (FSO, 2020) although rural areas are least represented due to less population and/or lower noise exposure. Finally, the data spans over a wide  $L_{den}$  range as well as a wide range of observed relative frequencies of HA. The distributions of the study sample per noise source, depicted geographically, as well as a function of the degree of urbanisation and of the  $L_{den}$  are shown in the supplemental material (Section S1). As a comparison, the distribution of the whole Swiss population as a function of the  $L_{den}$  is given in

Karipidis et al. (2014).

### 2.3. Residential green characterisation and assessment

In this study, a range of 22 “green metrics” were developed and/or used to characterize residential green (see Table 1), namely, “NDVI”, “LU-green”, “LU-natural”, “quiet and/or accessible green/natural spaces”, “visible vegetation from home”, and “landscape suitability for nearby recreation”, the latter introduced by Kienast et al. (2012). These metrics were assessed at the respondents' address, given by the x- and y-coordinates of the assigned dwelling unit, and then linked to the survey data.

All metrics were determined for four buffer sizes (radius of 150 m, 300 m, 500 m and 1,000 m), with the dwelling unit as its centre. The 500 m buffer size, which represents the local neighbourhood within walking distance, was defined *a priori* as the main area of influences based on other studies, such as by Villeneuve et al. (2012), Vienneau et al. (2017) and Dzhambov et al. (2018a, 2018b). We therefore focus on this buffer in the following. The other buffer sizes were only considered in sensitivity analyses.

All metrics were assessed with ArcGIS 10.6.1 (Esri Inc., Redlands, CA, USA), automated using the Python 2.7 “arcpy” module (Python Software Foundation, 2020). The metrics were calculated as follows:

**NDVI** is calculated from satellite-derived land surface reflectance, using cloud and snow-free Landsat scenes. NDVI takes values from  $-1$  to  $+1$ , where  $< 0.1$  represents barren areas (rock, sand, snow),  $0.2$ – $0.3$  represents shrub and grassland, and  $> 0.3$  indicates increasing greenness, i.e., higher and denser vegetation and/or forests (Weier and Herring, 2000). We used the Landsat 8 data of summer 2014 (seven tiles from 08 June to 19 July 2014 covering the whole of Switzerland), a time period of strong vegetation growth, as input to produce a dataset that was 100% cloud-free (spatial resolution:  $30 \times 30$  m). This data had been prepared and used by Vienneau et al. (2017). For each respondent, the mean NDVI of the buffer (value between  $-1$  and  $+1$ ) was calculated using the Python module “rasterio.mask”.

**LU-green** was assessed using data of the Federal Office of Topography (swisstopo). Where available, the most recent Swiss topographic landscape model was used (swissTLM<sup>3D</sup> 1.5, data of 2008–2016, accuracy of 1–3 m depending on the object). As the swissTLM<sup>3D</sup> does not include all natural areas, the data was complemented with the digital landscape model VECTOR25 (data of 1984–2005; accuracy of 3–8 m). LU-green was defined here as publically-available spaces that allow for recreation. It contains designated local and national parks as well as forest and agricultural areas. Agricultural areas were included, as due to their diversity in cultivations they are important recreational green spaces, often with public footpaths throughout. For each respondent, the fraction of the LU-green areas within the buffer area was calculated (in  $m^2/m_{\text{buffer}}^2$ , value between 0 and 1).

**LU-natural** was calculated as the sum of LU-green plus the area taken by lakes and rivers. The latter were derived from VECTOR25. Again, the fraction of LU-natural was calculated for each respondent (in  $m^2/m_{\text{buffer}}^2$ , value between 0 and 1).

**“Quiet” green and natural spaces** were assessed by considering only the fractions of low noise transportation pollution of the above green metrics. For the noise exposure characterization, we used the data of sonBASE, the Swiss-wide noise data base (FOEN, 2020). sonBASE provides rating levels ( $L_r$ ), separately for road, railway and air traffic, as calculated according to Swiss legislation (NAO, 1986), at a spatial resolution of  $10 \text{ m} \times 10 \text{ m}$ . The  $L_r$  corresponds to the A-weighted equivalent continuous sound pressure level ( $L_{\text{Aeq}}$ ), with the exception of railway noise where a level correction of  $-5$  to  $-15$  dB (“railway bonus”) is applied (see NAO, 1986, for details). We used the  $L_r$  for daytime of the year 2011, i.e., the exposure year of the SIRENE survey. From the  $L_r$  of the three sources, we calculated the total transportation noise exposure ( $L_{r_{\text{total}}}$ ). LU-green and LU-natural were

first rasterized to the  $L_{r_{\text{total}}}$  data raster. Only “quiet” raster cells ( $L_{r_{\text{total}}} < 50$ ,  $< 45$  or  $< 40$  dB) were retained, and their fraction (again in  $m^2/m^2$ , value between 0 and 1) was calculated for each respondent. To determine “quiet NDVI”, the raster cells exceeding a certain exposure ( $L_{r_{\text{total}}} \geq 50$ ,  $\geq 45$  or  $\geq 40$  dB) were set to 0, as if they were barren areas, thus ignoring any green/blue characteristics, and the mean value was calculated as above. The value of the resulting “quiet NDVI” decreases with increasing noise pollution within the buffer.

**“Accessible” LU-green and LU-natural** were quantified by means of walking time. For the characterization, we used the Swiss-wide road network data of OpenStreetMap (data of July 2018) Version API v.06 (SOSM, 2020). The network consists of edges and nodes. First, we estimated the mean slope of each edge as the altitude difference between corresponding nodes. Altitudes were determined with the digital height model DHM25 of swisstopo (spatial resolution of  $25 \text{ m} \times 25 \text{ m}$ ). Using the slopes, we then determined the walking speed using Tobler's hiking function (Tobler, 1993). Thereafter, the vertex of each LU-green and LU-natural polygon closest to the respondent was searched within the buffer, and the two closest nodes of the road network to the respondent's location and the vertex were determined. For these, the connecting path with the shortest walking time was obtained. Finally, using the inverse of the resulting walking times, the polygons were weighted and summed up using Eq. (1),

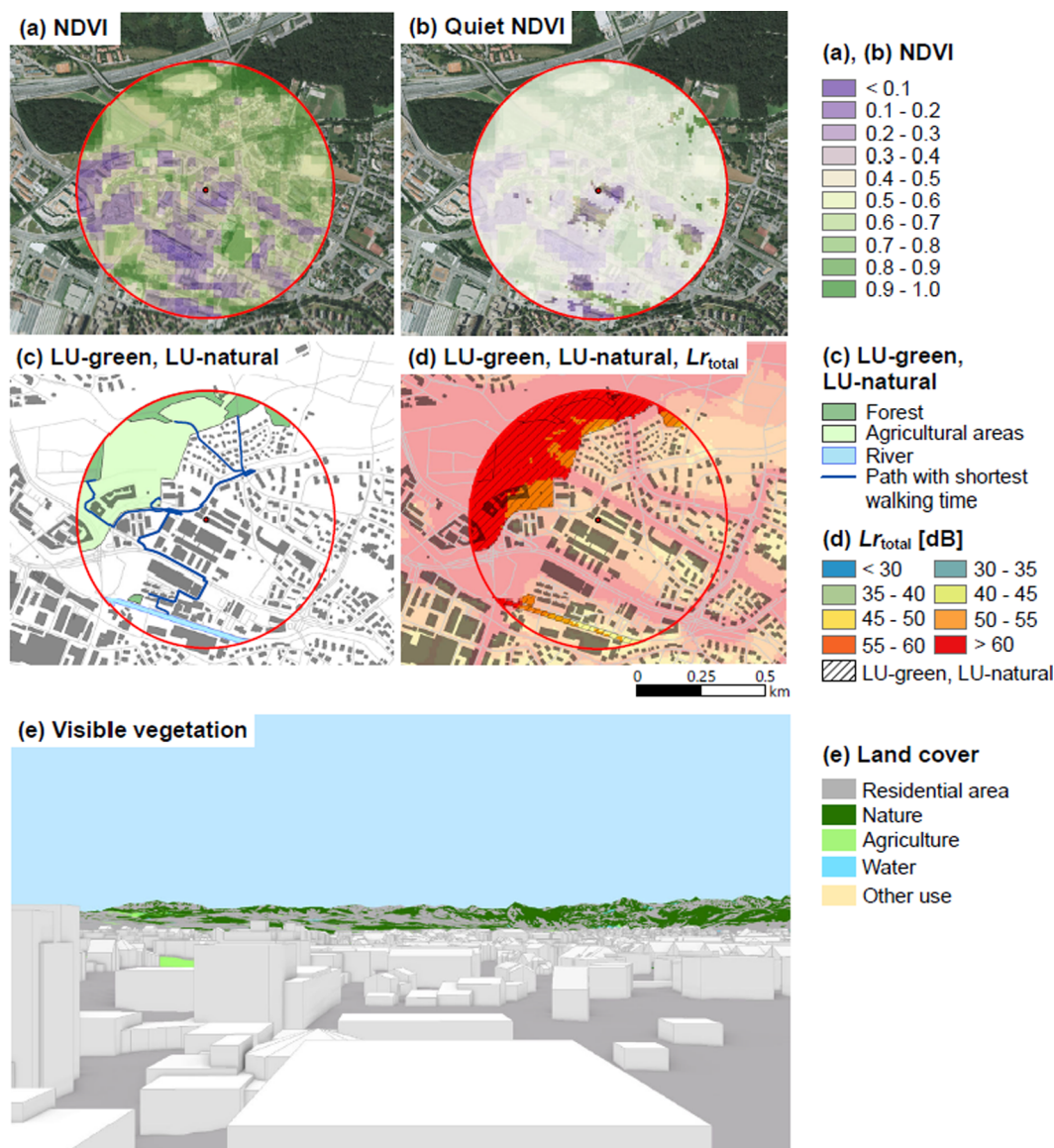
$$\left. \begin{array}{l} \text{Accessible LU-green} \\ \text{Accessible LU-natural} \end{array} \right\} = \sum_{i=1}^n \frac{F_i}{t_i^2} \times \left( \frac{F_B}{t_0^2} \right)^{-1} \quad (1)$$

where  $F_i$  and  $t_i$  are the area (in  $m^2$ ) and walking time (in s) of LU-green or LU-natural polygon  $i$ ,  $n$  is the number of polygons within the buffer,  $F_B$  is the total area of the buffer (in  $m^2$ ), and  $t_0$  is set to 1 s. An exponent of two was chosen for the weighting with walking time, as distance (and thus time) is a restrictive factor (Giles-Corti et al., 2005; Hansen, 1959). Thus, green spaces that are farther away from the respondent's dwelling unit, requiring longer walking times to reach them, are considered by a reduced overall value for “accessibility of green” of the respondent within the buffer. The factor  $(F_B/t_0^2)$  is used to normalize the sum in Eq. (1) to obtain the fraction of accessible green spaces (in  $m^2/m_{\text{buffer}}^2$ , value between 0 and 1) for each respondent.

**“Quiet” and “accessible” LU-green and LU-natural** (in  $m^2/m_{\text{buffer}}^2$ , value between 0 and 1) were obtained for each respondent by weighting the quiet areas with walking time as described above.

**Visible vegetation from home** was assessed with a viewshed analysis of the  $180^\circ \times 180^\circ$  display window for the loudest (and quietest) façade of each respondent's dwelling. The analysis considers the view to a distance of 50 km, which corresponds to the range of vision under very clear atmospheric conditions. While the visibility depends on atmospheric conditions, the chosen distance is not critical, as in most cases, obstacles (buildings, natural terrain) will limit the view to shorter distances. Buildings blocking the view were accounted for within a radius of 500 m (one buffer size only). For the analysis, the terrain model swissALTI<sup>3D</sup> (data of 2016) and the buildings model swissBUILDINGS<sup>3D</sup> 2.0 (data of 2017) of swisstopo (or swissTLM<sup>3D</sup> 1.6, data of 2016, where swissBUILDINGS<sup>3D</sup> 2.0 was not available) were used. Further, the land cover types were obtained from the digital landscape model VECTOR25 (data of 1984–2005, as above) of swisstopo, and reclassified into the five classes “water bodies” (lakes, rivers), “agriculture”, “nature”, “settlement areas” and “other use” (e.g., dam, quarry). Outside Switzerland, the terrain model of ASTER Global Digital Elevation Map (Version V2, data of 2011) (NASA, 2020), and the landscape model of CORINE Land Cover inventory (data of 2016) (CLMS, 2020) were used. The analysis yields the freely visible vegetation areas as the sum of agriculture and nature in the range of 0–100%. Nearby vegetation such as trees or shrubs were not included in the analysis, as such data was not available for the analysis on a national scale.

Finally, we used a metric for **landscape suitability for nearby**



**Fig. 2.** Residential green characterization for the 500 m buffer around the first author's (BS) office building at Empa, near Zürich, serving as an example. (a) NDVI, (b) quiet NDVI (rich colours, with rating sound level of the day  $Lr_{total} < 50$  dB), (c) LU-green (forest and agriculture) and LU-natural (LU-green plus water bodies) and paths with shortest walking time, (d) LU-green and LU-natural (shaded areas, in rich colours) including their noise exposure ( $Lr_{total}$ ), and (e) visible vegetation from office building ( $80^\circ \times 24^\circ$  display window; view  $119^\circ$  towards south-east, 5th floor, 18.5 m above ground). The corresponding values of the green metrics are given in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**recreation** developed by Kienast et al. (2012). This metric considers the distance between residence and recreational areas, the presence of open water, wetlands, forests, hills, hiking trails, accessible viewpoints, settlements and single objects that are attractive for outdoor recreation such as ruins, the absence of major roads, and the diversity of land use. The data set (spatial resolution of  $25\text{ m} \times 25\text{ m}$ ) shows the quality from low ( $< 1.5$ ) to high ( $> 4.5$ ) or very high values ( $> 7.5$ ), the latter representing hilly areas with a diverse land use, hiking trails and water bodies (Buchecker et al., 2013). With the raster cells representing a moving average of the above landscape characteristics over a  $1\text{ km}^2$  square ( $1000\text{ m} \times 1000\text{ m}$ , corresponding to a buffer of 500 m in perpendicular direction), we used the value of the raster cell corresponding to the respondent's address.

Fig. 2 shows the residential green characterization around Empa, for illustration purposes. Empa is located in an urban environment (degree of urbanization = cities). The green metrics corresponding to Empa's surroundings (Fig. 2) indicate that Empa's neighbourhood is quite green

(NDVI = 0.51), with about a quarter of the neighbourhood within the 500 m buffer consisting of LU-green ( $0.23\text{ m}^2/\text{m}^2$ ) and/or LU-natural ( $0.25\text{ m}^2/\text{m}^2$ ). However, only very few areas are well accessible ( $\ll 0.01\text{ m}^2/\text{m}^2$ ), and only little green is visible towards south-east ( $\sim 1\%$ ). Further, Empa's neighbourhood is strongly exposed to road traffic and railway noise. Only a small fraction of LU-natural is rather quiet ( $Lr_{total} < 50$ :  $0.01\text{ m}^2/\text{m}^2$  quiet LU-natural, no quiet LU-green), and there are no well-accessible quiet areas around Empa. With a value of 3.4, landscape suitability for nearby recreation is medium.

#### 2.4. Statistical analysis

The present study aimed at establishing ERCs reflecting the probability of high annoyance (PHA) as a function of exposure to transportation noise ( $L_{den}$ ) and to green metrics (Table 1), separately for the noise sources road, rail and air, thereby also considering the degree of urbanization and personal characteristics. ERCs were established by

means of logistic regression analysis.

Contrary to Brink et al. (2019a), who carried out separate analyses for road traffic, railway and aircraft noise, we established a single statistical model for all three noise sources. While the two modelling approaches yield equivalent results, our approach has the advantage that the effects of certain predictors (e.g., personal characteristics) only need to be estimated once and that the effects of the noise sources can be compared with each other within a single model. However, the resulting model is more complex. Further, as the noise annoyance data has a hierarchical structure (1–3 annoyance ratings per respondent, depending on the number of noise sources the respondents were simultaneously exposed to), the correlation of the data within respondents needs to be accounted for. This was done by using a hierarchy of levels, the upper level being the respondents and the lower level being the 1–3 annoyance ratings per respondent. To do so, we used generalized estimating equations (Liang and Zeger, 1986). They yield a population-averaged response (Hu et al., 1998; Schäffer et al., 2017).

The hierarchical structure of the observations was accounted for by an exchangeable working correlation structure, which assumes uniform correlations within individuals (Jang, 2011). The assumption of the working correlation matrix is not critical, as the parameter estimates are consistent even if the assumed working correlation matrix would be misspecified (Hu et al., 1998; Zeger et al., 1988).

As main predictors, the model considers the noise source,  $L_{den}$ , and one of the green metrics. The green metrics were serially examined in different models, i.e., not within the same model, to avoid multicollinearity. Further, based on the results obtained by Brink et al. (2019a) regarding the effects of personal characteristics on annoyance, sex, home ownership, interview language and age (linear and quadratic term) were a priori included as personal characteristics. (Testing a range of possible personal characteristics was beyond scope of this study). Contrary to Brink et al. (2019a), interview mode (postal vs. online) was not included, as it did not significantly affect the ERCs ( $p = 0.81$ ). In addition, we investigated whether adding the degree of urbanization to the ERCs modifies the relationship between pHA and the green metrics (strength and/or direction). Finally, different interactions between noise source,  $L_{den}$ , green metric and/or degree of urbanization were tested.

Thus, the ERCs were established by exploratory data analysis. A large number of models of different degrees of complexity was tested. The main models are described in Section 2.5. The models were compared to each other with respect to completeness (include all relevant variables), significance of effects (considered as a probability value of the null hypothesis  $\leq 0.05$ ) and parsimony. For the latter, we used the corrected quasi-likelihood under the independence model criterion (QICu, referred to as QICC in SPSS) (Pan, 2001) as a goodness of fit criterion. The model with the smallest QICu is preferred.

Potential multicollinearity of the predictor variables was evaluated by means of correlation matrixes and with the variance inflation factors (VIF: see, e.g., Kutner et al., 2004). As the models contain categorical predictors with different numbers of levels, we calculated  $GVIF^{1/(2 \times df)}$  according to Fox and Monette, (1992), where GVIF is the generalized VIF and df is the degrees of freedom of the variables. In this analysis, the quadratic term of age and all interaction terms were excluded.

Statistical analysis was carried out with IBM SPSS Version 25.  $GVIF^{1/(2 \times df)}$  were calculated using the package “car” in R Version 3.5.1 (R Foundation for Statistical Computing, Vienna, Austria).

**Separation of noise vs. residential green effects:** It is important to note that the analysed data set covers a wide range of  $L_{den}$  (low to high; Section 2.1) and green metrics (“not much” to “a lot of” green; Table 1), as well as their combinations (i.e., noisy situations in green environments, quiet situations in non-green environments etc.). The statistical modelling approach therefore allows separating the individual contribution of noise exposure and residential green on noise annoyance, as well as possible interactions between the two. Thus, any

effect of green metrics on annoyance as disclosed in this study persists beyond simply reducing the noise level in greener areas. It is attributed to the vegetation and green environment.

## 2.5. Exposure-response curves

In this study, a crude model (Model 0) plus the following three further Models 1–3 were explored and compared for the green metrics.

**Model 0:** Crude model:

$$\text{logit(pHA)} = \beta_0 + \tau_{\text{Src},i} + \beta \times L_{\text{den},ij} + \beta_{\text{Src},i} \times L_{\text{den},ij}, \quad (2)$$

where  $\text{logit(pHA)}$  is the logit link function of pHA,  $\beta_0$  is the overall mean,  $\tau_{\text{Src}}$  is the categorical variable noise source (3 levels:  $i =$  road, rail, or air),  $L_{\text{den}}$  is the continuous variable day-evening-night level,  $\beta$  is the regression coefficient for  $L_{\text{den}}$ , and  $\beta_{\text{Src}} \times L_{\text{den}}$  represents an interaction term between noise source and  $L_{\text{den}}$ . With the  $\tau_{\text{Src}}$  set to the specific noise source (road, rail, air), pHA represents the annoyance as a function of the  $L_{\text{den}}$  of the chosen source. The interaction term accounts for different (noise source specific) slopes of the ERCs. The index  $ij$  stands for the  $j$ th observation of the  $i$ th noise source. The coefficients of Model 0 are given in the supplemental material (Section S2). Model 0 yields very similar ERCs as the three separate crude models for road, rail, and air developed by Brink et al. (2019a) (see supplemental material, Section S3). This confirms that the two modelling approaches yield equivalent results.

**Model 1** extends Model 0 to also account for the (noise source specific) effects of residential green on annoyance, as well as for personal characteristics. **Model 2** is similar to Model 1, but additionally considers the fact that the effects of residential green may depend on the level of  $L_{\text{den}}$ , in addition to the noise source. The equations of Models 1 and 2 are given in the supplemental material (Section S4).

Finally, **Model 3** extends Model 0 to account for the (noise source specific) effects of residential green and personal characteristics (as Model 1), but also for the degree of urbanization as a potential effect modifier:

$$\begin{aligned} \text{logit(pHA)} = & \beta_0 + \tau_{\text{Src},i} + \beta \times L_{\text{den},ijk} + \gamma \times M_{\text{green},ij} + \tau_{\text{DegUrba},j} \\ & + \beta_{\text{Src},i} \times L_{\text{den},ijk} + \gamma_{\text{Src} \times \text{DegUrba},ij} \times M_{\text{green},ij} + \text{PersChar}, \end{aligned} \quad (3)$$

where  $M_{\text{green}}$  is the green metric (Table 1),  $\gamma$  is its regression coefficient,  $\tau_{\text{DegUrba}}$  is the categorical variable degree of urbanization (3 levels:  $j =$  cities, towns & suburbs, or rural areas),  $\gamma_{\text{Src} \times \text{DegUrba}} \times M_{\text{green}}$  represents a 3-fold interaction term between  $\tau_{\text{Src}}$ ,  $\tau_{\text{DegUrba}}$  and  $M_{\text{green}}$ ,  $\text{PersChar}$  symbolizes the personal characteristics (five additional terms, i.e., two continuous variables age and age<sup>2</sup> plus three categorical variables sex, language and home ownership), the index  $ijk$  stands for the  $k$ th observation of the  $i$ th noise source and the  $j$ th degree of urbanization, and the other terms keep their above notations. The 3-fold interaction accounts for the fact that the effect of  $M_{\text{green}}$  may depend on  $\tau_{\text{DegUrba}}$ , which may in turn depend on the noise source.

For the range of tested green metrics, model preference with respect to (increasing) QICu decreased in the order Model 3 > Model 1 > Model 2. Models 1 and 3 performed better than Model 0. Given the model performance, and because we were interested in the degree of urbanization, we chose Model 3 and present these results in the following account, unless otherwise specified. With values of 1.00–1.24, the  $GVIF^{1/(2 \times df)}$  of all green metrics indicate that no multicollinearity was present.

## 3. Results

### 3.1. Green metrics: Value range, correlations and distributions

Table 1 presents the value range covered by the study sample (percentile values). Correlation analysis (see supplemental material,

Section S5) revealed that, except for landscape suitability for nearby recreation, the green metrics of Table 1 were moderately to highly positively correlated with each other. For the 500 m buffer, Pearson's  $r$  ranged from 0.22 to 0.99, depending on green metric, while landscape suitability for nearby recreation was only little correlated with the other metrics ( $r = -0.03$  to  $+0.19$ ). As expected, the correlations between metrics also somewhat depended on the buffer size (not shown). Within metrics, the correlations between different buffer sizes were high (e.g., NDVI:  $r = 0.69$ – $0.95$ ). Further, residential green, and thus the values of the green metrics, is related to the degree of urbanization, increasing in the order cities < towns and suburbs < rural areas (see supplemental material, Section S6, for NDVI). Finally, the metrics were mostly low and negatively correlated with the  $L_{den}$  ( $r = -0.56$  to  $0.18$  for the 500 m buffer), i.e., greener areas are generally quieter. The “quiet” metrics showed somewhat higher negative correlations with the  $L_{den}$  than the other metrics.

The green metrics were partly strongly skewed (see supplemental material, Section S7). Skewness tended to increase with decreasing buffer size (except for NDVI, the distribution of which remained quite stable), and/or for quiet areas with decreasing  $L_{total}$ , and/or for accessible areas.

### 3.2. Association between residential greenness and noise annoyance

For Model 3, the following green metrics were found to be best suited to describe the effects of residential green on annoyance: NDVI > LU-green  $\approx$  LU-natural. We therefore focus on NDVI and LU-green in the following. The supplemental material (Section S8) gives a detailed account of the performance of all metrics. In Section S9, it further presents the resulting coefficients of Model 3 for NDVI and LU-green, as well as “aggregated” coefficients of all green metrics of Table 1 as derived from Model 3. The latter represent the ERCs for pHA as a function of the  $L_{den}$ , separately for the 5th, 50th and 95th percentile of the green metrics, and allow re-drawing the ERCs presented in this section.

Fig. 3 shows the modelled ERCs for pHA (centred over the degree of urbanization) as a function of residential green, exemplarily at an  $L_{den}$  of 60 dB. Green is clearly associated with noise annoyance for all three traffic sources, with NDVI showing a stronger effect than LU-green. For road traffic noise, green strongly reduces noise annoyance. The same holds true for railway noise, although decreasing annoyance with increasing green can only be observed for NDVI. For aircraft noise, in

contrast, residential green is strongly associated with increased noise annoyance. In particular, with an increase in NDVI from 0 to 1, pHA increases from  $\sim 0.1$  to 0.7. However, 90% of NDVI observed within the SiRENE survey sample is contained within a range of 0.33–0.72 (between 5th and 95th percentile), which corresponds to a narrower pHA range of  $\sim 0.2$ – $0.5$ .

Fig. 4 shows the modelled ERCs for pHA (centred over the degree of urbanization) as a function of the  $L_{den}$  and residential green. The ERCs are drawn for the 5th, 50th and 95th percentile of the green metrics (Table 1), representing neighbourhoods with little, average and a lot of residential green. The strong effect of green on noise annoyance (Fig. 3) leads to a shift of the ERCs in Fig. 4 on the abscissa ( $L_{den}$ ) between the 5th and 95th percentile curves, while the slopes remain unchanged. This can be interpreted as an equivalent sound pressure level change ( $\Delta L$ ).  $\Delta L$  depends on noise source and green metric (Table 2). As an example: NDVI is associated with reduced road traffic and railway noise annoyance, but with increased aircraft noise annoyance. Road traffic noise annoyance of those respondents whose NDVI was only 5% of the sample distribution (i.e., “not much green”), was the same at a 6.3 dB lower  $L_{den}$  than of those whose NDVI was 95% (“a lot of green”). In other words, those whose residential green was close to the maximum possible value were, on average, equally annoyed only at a substantially larger  $L_{den}$  than those whose green was close to the minimum.

For road traffic noise (Fig. 4 left panels),  $\Delta L$  takes large values of  $-6.3$  to  $-0.8$  dB (i.e., annoyance reduction, Table 2). In fact, separate logistic regression analysis for road traffic noise alone revealed that most green metrics significantly reduced noise annoyance ( $p < 0.05$ ; Table 2). Interestingly, LU-natural yields somewhat smaller  $\Delta L$  than LU-green. For railway noise (Fig. 4 middle panels), with  $\Delta L$  ranging from  $-3.6$  to  $+1.5$  dB the effect of residential green was less clear. Also separate logistic regression revealed significant effects for NDVI and landscape suitability for nearby recreation only ( $p < 0.05$ ; Table 2). For aircraft noise, in contrast,  $\Delta L$  with values  $+0.8$  to  $+10.7$  dB was largest of all three sources, indicating an annoyance increase (Fig. 4 right panels). Separate logistic regression revealed that most green metrics were significantly associated with increased noise annoyance ( $p < 0.05$ ; Table 2).

The sensitivity analysis on buffer size confirmed that the observed effects of residential green on annoyance were similar between buffers, and that a 500 m buffer seems appropriate for all metrics (see supplemental material, Section S10).

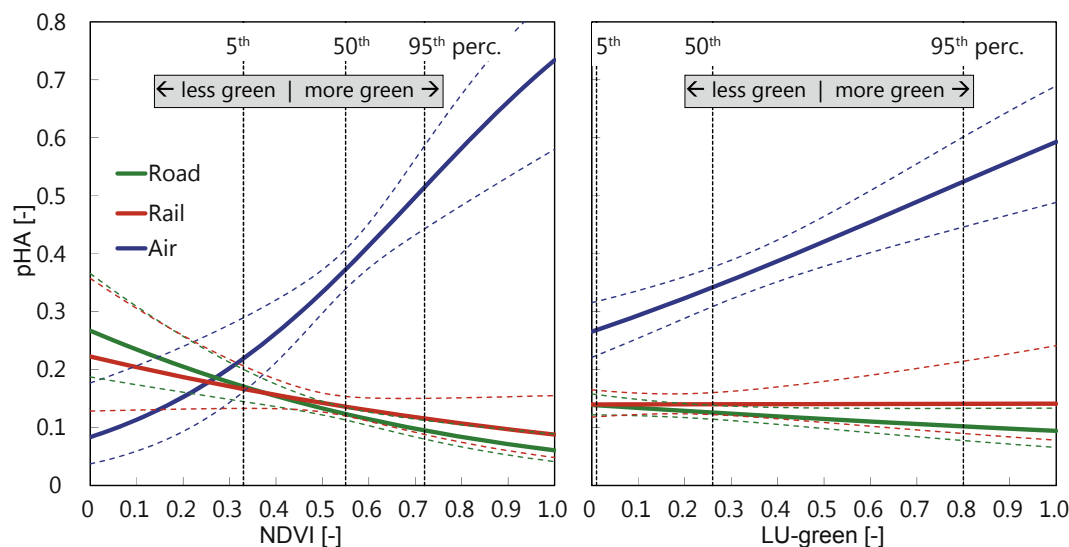
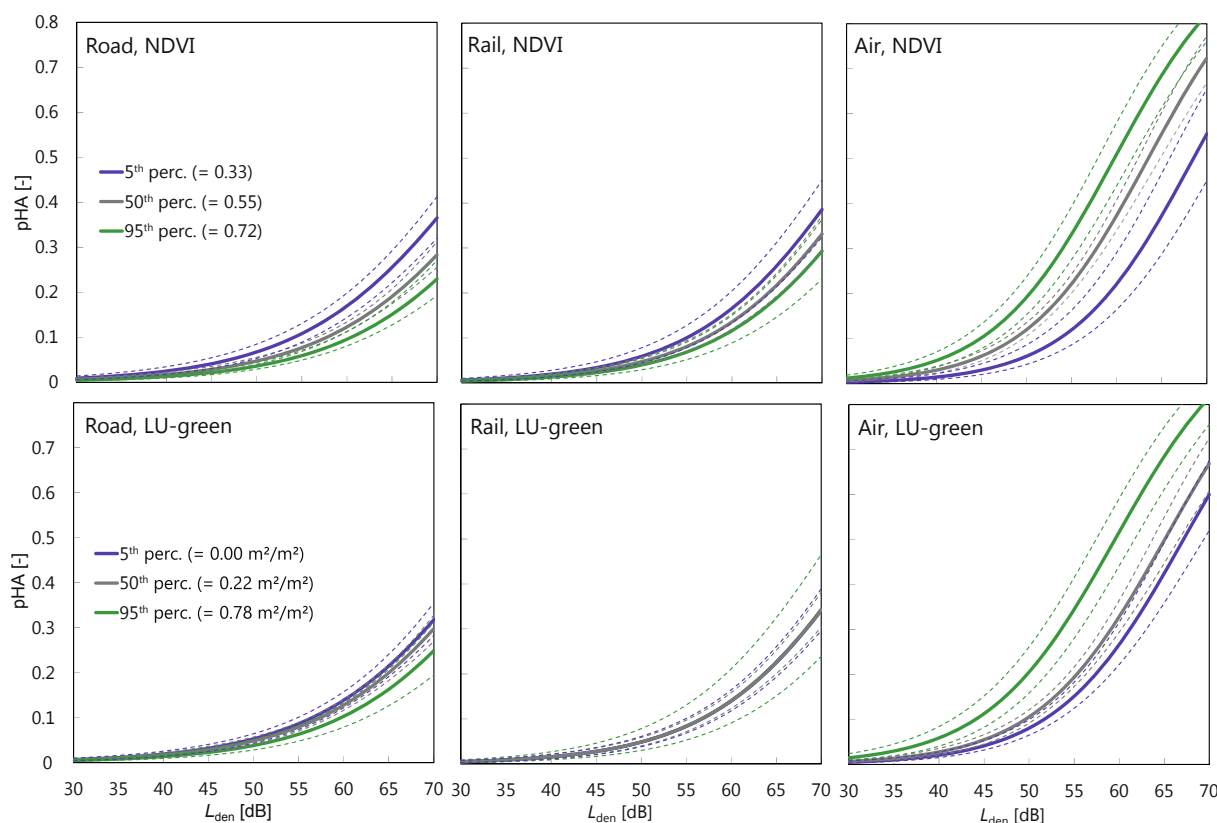


Fig. 3. Exposure-response curves [Model 3, Eq. (3)] for the probability of high annoyance (pHA) at an  $L_{den}$  of 60 dB as a function residential green (left: NDVI, right: LU-green) for road traffic, railway and aircraft noise, including 95% CI. The curves are centred on all covariates. Further, the 5th, 50th and 95th percentiles (Table 1) are drawn. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Exposure-response curves [Model 3, Eq. (3)] for the probability of high annoyance (pHA) as a function the  $L_{den}$  and residential green (top: NDVI, bottom: LU-green) for road traffic (left), railway (middle) and aircraft noise (right), including 95% CI. The three curves per plot represent the 5th, 50th and 95th percentiles (values: Table 1). They are centred on all covariates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**

Equivalent sound pressure level change ( $\Delta L$ , in dB) of noise annoyance associated with an increase in residential green from the 5th to 95th percentile. Negative values indicate a decrease in noise annoyance with increasing residential green, whereas positive values indicate an increase.  $\Delta L$  between exposure-response curves with non-overlapping CI are highlighted in bold.

Green metric	$\Delta L$ of Noise Source [dB]		
	Road	Rail	Air
NDVI	<b>-6.3*</b>	-3.6*	<b>+8.8*</b>
Quiet NDVI ( $L_{r_{total}} < 50$ dB)	-3.9*	+0.5	<b>+7.3*</b>
Quiet NDVI ( $L_{r_{total}} < 45$ dB)	-1.8*	+0.5	<b>+7.5*</b>
LU-green	-3.2*	+0.1	<b>+7.6*</b>
Quiet LU-green ( $L_{r_{total}} < 50$ dB)	-3.2*	-0.4	<b>+9.6*</b>
Quiet LU-green ( $L_{r_{total}} < 45$ dB)	-3.0*	+0.3	<b>+10.7*</b>
Accessible LU-green	-4.4	-3.4	<b>+3.5*</b>
Quiet & accessible LU-green ( $L_{r_{total}} < 50$ dB)	<b>-5.5*</b>	- <sup>a</sup>	+5.1
Quiet & accessible LU-green ( $L_{r_{total}} < 45$ dB)	- <sup>a</sup>	- <sup>a</sup>	- <sup>a</sup>
LU-natural	-1.5	+1.3	<b>+7.9*</b>
Quiet LU-natural ( $L_{r_{total}} < 50$ dB)	-2.0*	+1.3	<b>+9.3*</b>
Quiet LU-natural ( $L_{r_{total}} < 45$ dB)	-2.0*	+1.5	<b>+10.3*</b>
Accessible LU-natural	-4.6	-3.6	<b>+3.5*</b>
Quiet & accessible LU-natural ( $L_{r_{total}} < 50$ dB)	-6.1	- <sup>a</sup>	+5.2
Quiet & accessible LU-natural ( $L_{r_{total}} < 45$ dB)	- <sup>a</sup>	- <sup>a</sup>	- <sup>a</sup>
Visible vegetation from home <sup>b</sup>	-1.6	-1.2	+2.6*
Landscape suitability for nearby recreation	-0.8	-3.6*	+0.8*

<sup>a</sup> Model cannot be (reliably) estimated (see supplemental material, Section S8).

<sup>b</sup> View from loudest façade.

\* Significant effect of the green metric ( $p < 0.05$ ) according to separate logistic regression for the respective noise source.

### 3.3. Effect modification by degree of urbanisation

While the effects of the “basic” metrics NDVI, LU-green and LU-natural did not strongly change with the degrees of urbanization (not shown), their derivatives (accessible and/or quiet areas), and visible vegetation from home did. Results are as follows:

#### 3.3.1. Road traffic noise

Fig. 5 shows the ERCs of quiet LU-green, accessible LU-green, and visible vegetation from home for road traffic noise per degree of urbanization. Quiet residential green seems to particularly strongly reduce annoyance in rural areas ( $\Delta L = -9.6$  dB), while accessible green is strongly linked to reduced annoyance in cities ( $\Delta L = -8.8$  dB). Similar results as for quiet LU-green were also found for quiet NDVI and quiet LU-natural. Further, quiet and accessible green spaces (LU-green or LU-natural) combined the effects of quiet LU-green and accessible LU-green. They showed a strong effect in both urban and rural areas. Visible vegetation from home was associated with reduced annoyance in cities ( $\Delta L = -3.5$ ), but not in towns and suburbs or rural areas.

#### 3.3.2. Railway noise

For railway noise, the dependence of the effects of residential green on the degree of urbanization was less clear. This was expected, given the limited and mostly non-significant overall effects of residential green (Section 3.2). Only accessible LU-green and LU-natural tended to be more important in urban than in rural areas.

#### 3.3.3. Aircraft noise

For aircraft noise, the degree of urbanization most noticeably modified the association between quiet LU-green or visible vegetation from home and annoyance (Fig. 6). The effect of both metrics were



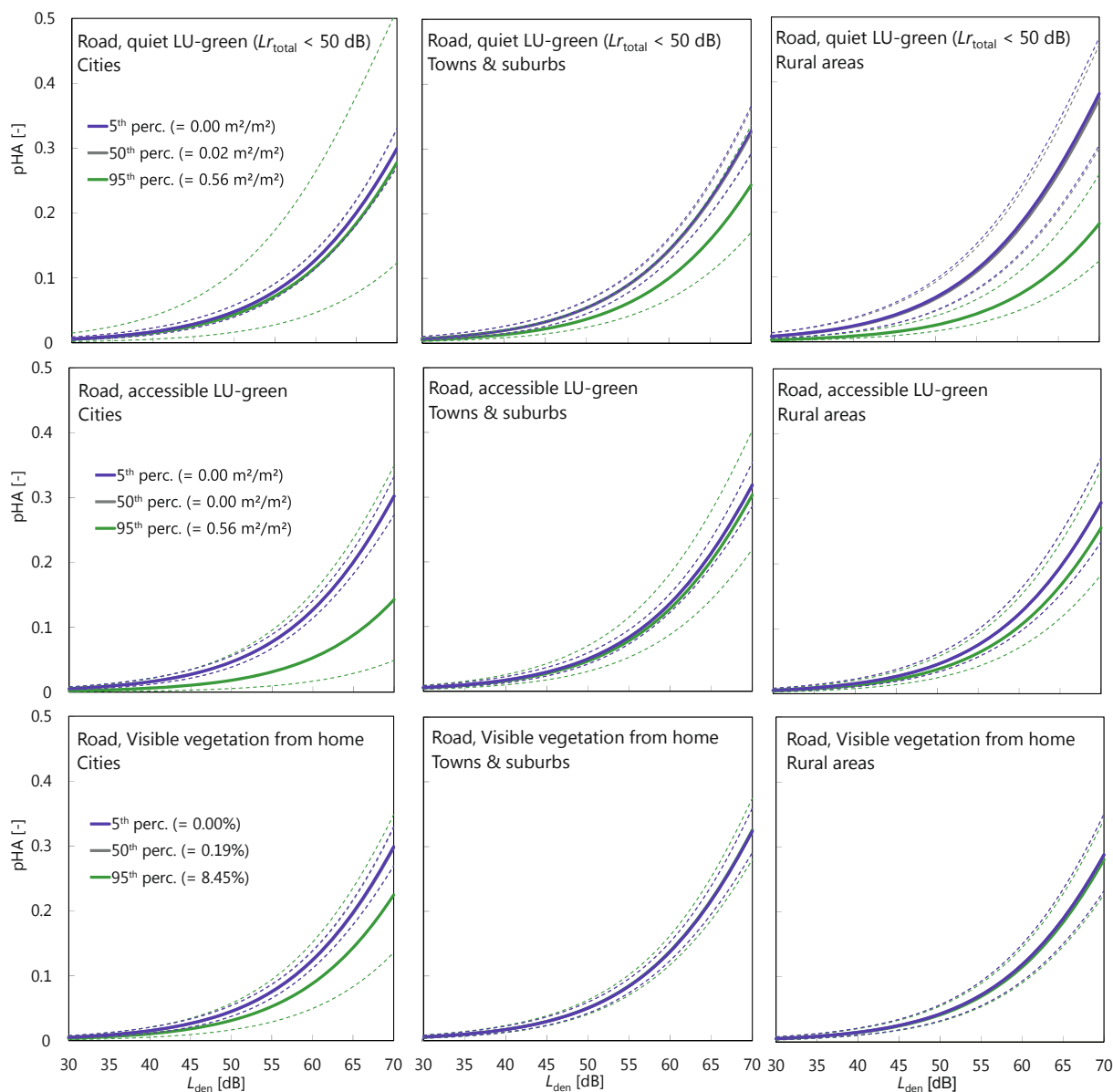


Fig. 5. Exposure-response curves [Model 3, Eq. (3)] for the probability of high annoyance (pHA) for road traffic noise as a function the  $L_{den}$ , residential green (top: quiet LU-green with  $L_{r_{total}} < 50$  dB, middle: accessible LU-green, bottom: visible vegetation from home, loudest façade) and degree of urbanization (left: cities, middle: towns and suburbs; right: rural areas), including 95% CI. The three curves per plot represent the 5th, 50th and 95th percentiles (values: Table 1). They are centred on all covariates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

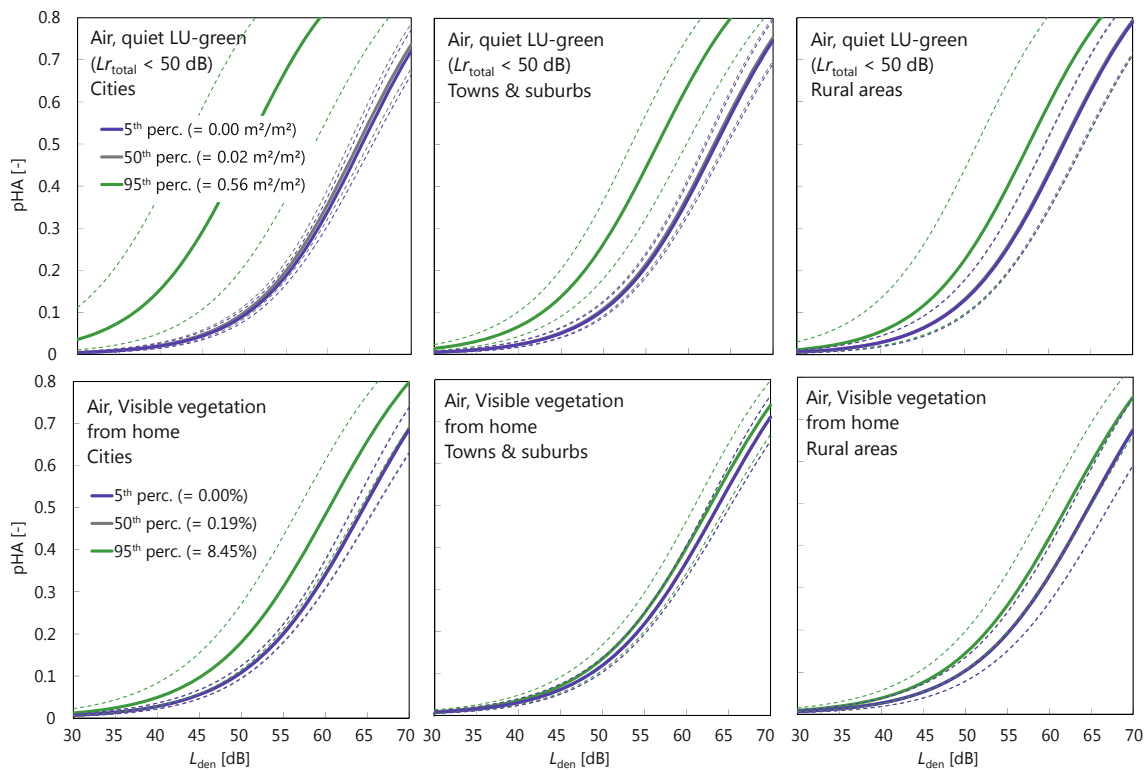
strongest in cities (quiet LU-green:  $\Delta L = +13.7$ ; visible vegetation:  $\Delta L = +4.1$ ). For quiet LU-green, this contrasts the findings for road traffic noise that the effect was most pronounced in rural areas (Fig. 5).

In interpreting the above results, one should consider the lack of overall significance of the effects of accessible LU-green and visible vegetation from home in the case of road traffic noise (Table 2). Further, both Figs. 5 and 6 show that the 95th percentile curves have large CIs in cities, i.e., the association of green and annoyance is afflicted with increased uncertainty. Further, the 5th and 50th percentile curves and their CI are almost congruent for some green metrics, which is due to their skewed distribution.

### 3.4. Effects of residential green at different noise exposures

In this section we explore, exemplarily for NDVI, if the effect of residential green depends on  $L_{den}$ . Fig. 7 shows the observed relative frequencies of pHA as a function of the  $L_{den}$ , for two classes of NDVI

( $> 0.5$  or  $\leq 0.5$ ). At “low”  $L_{den}$  (road traffic  $< 55$  dB, railway  $< 50$  dB, aircraft  $< 40$  dB), the effect of NDVI on HA seems indeed negligible for all three noise sources. Above these  $L_{den}$  values, the effect of NDVI on annoyance is clearly observable. For road traffic noise, no “upper limit” can be discerned over the whole  $L_{den}$  range (Fig. 7 left). In contrast, for railway and aircraft noise annoyance (Fig. 7 middle and right) the effect of NDVI seems to become small at “high”  $L_{den}$  (railway noise  $> 70$  dB, aircraft noise  $> 60$  dB). However, due to the relatively small number of observations at high  $L_{den}$  (see supplemental material, Section S1), the upper limit for the effect of NDVI cannot be reliably determined. Thus, at least for the  $L_{den}$  range to which most of the respondents were exposed, no upper limit seems to have played a role. Also, while the ERCs of Model 2 (Section 2.5) are not perfectly parallel, the interaction between NDVI and  $L_{den}$  is weak. Accordingly, the ERCs of Models 2 and 3 are quite similar (see supplemental material, Section S11), although Model 3 assumes that the effect of residential green does not depend on  $L_{den}$ . Model 3 is therefore



**Fig. 6.** Exposure-response curves [Model 3, Eq. (3)] for the probability of high annoyance (pHA) for aircraft noise as a function the  $L_{den}$ , residential green (top: quiet LU-green with  $L_{r_{total}} < 50$  dB, bottom: visible vegetation from home, loudest façade) and degree of urbanization (left: cities, middle: towns and suburbs; right: rural areas), including 95% CI. The three curves per plot represent the 5th, 50th and 95th percentiles (values Table 1). They are centred on all covariates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

appropriate to describe the effects for residential green observed here.

#### 4. Discussion

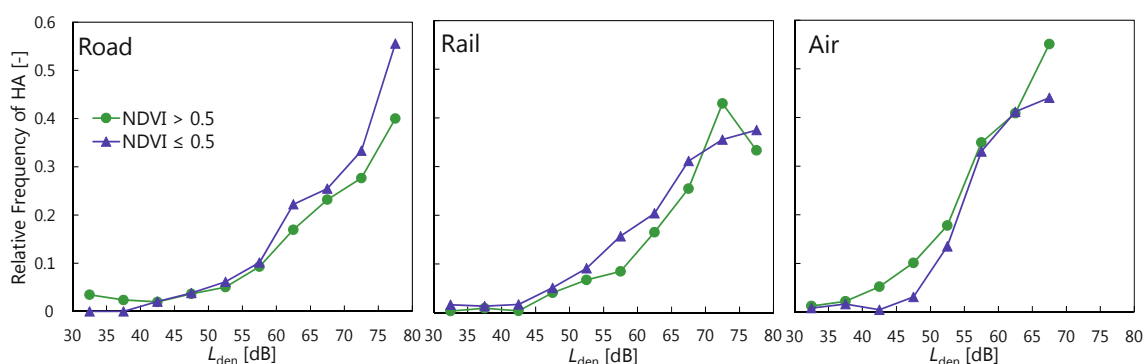
##### 4.1. Synthesis

In this study, the individual contributions of noise exposure and green exposure to noise annoyance were studied, separately for road traffic, railway and aircraft noise. The effects of residential green on annoyance as disclosed here go beyond simply reducing the noise level in green spaces; rather, they may be attributed to the vegetation and green environment.

**Road traffic and railway noise annoyance:** Our study confirms findings from literature that residential green is an important modifier for road traffic and railway noise annoyance (Dzhambov, 2017; Van Renterghem, 2019). In general, we found that residential green reduces

annoyance to these noise sources. The effect corresponds to an equivalent level reduction of  $\sim 6$  dB for road traffic and  $\sim 3$  dB for railway noise (Table 2) when green increases from “not much” to “a lot of” green (5th to 95th percentile). The level reduction for road traffic noise is similar to the 5 dB mentioned by Lercher (1996), but smaller than the 10 dB estimated by Van Renterghem (2019). However, the latter study focused on urban areas, while our values represent an “overall green effect”. For cities, some green metrics showed more pronounced effects, such as accessible LU-green with  $\sim 9$  dB (Fig. 5). These health-promoting effects may be due to fostering of physical activity and social cohesion, as well as restoration (Markevych et al., 2017; Van Renterghem, 2019).

From the tested green metrics, NDVI was found to be the strongest modifier for annoyance, followed by LU-green and LU-natural, over all degrees of urbanization. Their derivatives (accessible and/or quiet green spaces) as well as visible vegetation from home and landscape



**Fig. 7.** Observed (“raw”) relative frequencies (unadjusted for covariates) of high annoyance of the SiRENE survey sample as a function of the  $L_{den}$  (in bins of 5 dB) and NDVI (two classes,  $NDVI > 0.5$  and  $\leq 0.5$ ) for road traffic (left), railway (middle) and aircraft noise (right).

suitability for nearby recreation had lower predictive power. Thus, the more sophisticated metrics did not help in establishing stronger general associations between green and annoyance. Pronounced effects of NDVI and LU-green on road traffic noise annoyance were also reported by Dzhambov et al. (2018b) and Gidlöf-Gunnarsson and Öhrström (2007), respectively. Interestingly, LU-green was equally or even more associated with annoyance than LU-natural. Apparently water bodies only little affected annoyance in our study. Possibly the range of blue spaces covered here was too small to reveal this effect, with too few people in the study sample residing within proximity to blue spaces. Also the accuracy of 3–8 m of the underlying VECTOR25 data set might have played a (minor) role. However, also Leung et al. (2017) found that view on green reduces annoyance more than view on water bodies. We could not reproduce the particularly strong effect of visible vegetation from home reported by Van Renterghem (2019). However, this is likely due to the fact that (self-reported) view includes nearby vegetation (e.g., trees, shrubs), which was not accounted for by our metric. In fact, Mueller et al. (2020) found reduced road traffic noise annoyance in urban areas to be associated with residential tree cover density.

Visible vegetation from home was still found to be important in urban areas for road traffic noise, but not in towns and suburbs or rural areas. The same is true for accessible green spaces. The important role of accessible green spaces in urban areas to reduce noise annoyance was also reported by Gidlöf-Gunnarsson and Öhrström (2007). In contrast to the findings by Dzhambov and Dimitrova (2015), however, the closest distance (both network and Euclidian) and/or network walking time as metrics on their own were not conclusive predictors for noise annoyance in our study. The same, however, was also found by Dzhambov et al. (2018b). Contrary to accessibility, quiet green spaces were efficient in reducing noise annoyance in rural areas. This may be due to expectations regarding the soundscape. Residents expect congruency between acoustical and visual characteristics (e.g., Carles et al., 1999), so that green spaces should be “less noisy” in rural than urban areas. While the effects of certain quality attributes depend on whether residents live in urban or rural areas (and thus, over all degrees of urbanization had less predictive power), the fundamental “the greener the better”, at a given noise exposure, is generally true at a population level for the “basic” NDVI, LU-green and LU-natural. A good predictive power of the metrics NDVI and LU-green at a population level was also observed, e.g., by Vienneau et al. (2017).

**Aircraft noise annoyance:** Unexpectedly, increasing residential green was found to be strongly associated with increased aircraft noise annoyance (up to ~10 dB, Table 2). This is in line with the findings of Brink et al. (2019b) that self-reported sleep disturbance due to aircraft noise was higher in rural areas (with more green) than in urban areas (with less green). Here, one should note that both outcomes (annoyance as used here, and self-reported sleep disturbance as used in Brink et al. (2019b)) come from the same survey, and that the two outcomes may be at least partly related constructs. Similarly, Chau et al. (2018), in a laboratory study on annoyance to combined road traffic and sea sounds, found that view on mountain greenery could increase annoyance. Our findings, however, contrast the results from a laboratory experiment that vegetation may improve the perceived quality of an urban soundscape with aircraft noise events (Lugten et al., 2018).

Several special features of aircraft noise might explain our findings. First, while road traffic noise is an inherent acoustic feature of most residential areas, aircraft noise is more alien and intrusive. Second, road and rail traffic can more easily be evaded than aircraft noise. Residents may “escape” the traffic noise within quiet areas of green spaces, which fosters restoration. Aircraft, in contrast, may overfly green spaces, depriving residents of the possibility to escape aircraft noise. This might increase annoyance. Third, the intrusiveness of aircraft noise may contrast expectations of green spaces. Incongruence of sound and landscape is unfavourably perceived (e.g., Carles et al., 1999). This might explain the strong annoyance reactions sometimes observed in rural areas in the presence of aircraft noise. It could also be the reason

that relatively quiet green spaces in cities (where aircraft flyovers are potentially audible) were particularly strongly linked to increased aircraft noise annoyance (Fig. 6). Finally, also source visibility might play a role, as aircraft are not shielded by vegetation. However, Van Renterghem (2019) concluded that this effect is rather minor compared to the effects of residential green.

**Residential green at varying noise exposure:** We found that the association of residential green with annoyance was quite stable over a wide range of  $L_{den}$ , and an “upper limit” for the effect of greenness could not be reliably determined. From literature, one would expect stronger effects at medium than at low (Van Renterghem, 2019), or high levels (Aylor and Marks, 1976). However, Bodin et al. (2015) also did not find a pronounced change in the effect of having a quiet side (defined as a “window facing yard, water or green space”) on annoyance over a wide  $L_{Aeq}$  range. Our data thus suggests that, for relevant environmental noise exposure ranges, the modifying effect of residential green is quite stable.

#### 4.2. Strength and limitations

To our knowledge, this is the first time that the effects of residential green on transportation noise annoyance was studied, separately for road traffic, railway and aircraft noise annoyance. Strengths of the underlying annoyance survey data set (sample size, stratification of the sample, level of detail of the noise calculations, consideration of seasonal differences in annoyance, etc.) are discussed by Brink et al. (2019a). The set of green metrics, ranging in complexity, acquired on a national scale for almost 5600 respondents is an additional asset of this study.

Nevertheless, some limitations of our study should be considered in interpreting the results. First, for the underlying annoyance data two primary limitations were identified, namely the response rate of 31% (which, however, lies well within the expected range) and the gap between exposure assessment and survey years (2011 vs. 2014/2015) (Brink et al., 2019a). A gap also applies to the green metrics (available data bases mostly of 2008–2018, partly of 1984–2005), but they will not have notably changed over this time period. Second, the survey sample had been stratified based on noise exposure (Brink et al., 2019a). For the present study, a stratification including also residential green would have been favourable, but had not been possible as we used existing annoyance data. Our study might thus particularly represent the Swiss setting, which may be considered somewhat unique in terms of greenness. Nevertheless, our findings should still be transferable to other countries, possibly except for the range of the metrics (between 5th and 95th percentiles) which may differ from other countries. Third, our quantification of visible vegetation only partly represents what residents see from home, as it only accounts for freely visible agricultural and natural areas. It neglects nearby vegetation in the local living environment (e.g. trees, shrubs). This is likely the reason why we found a substantially weaker effect on road traffic noise annoyance (~1.5 dB overall; ~3.5 dB in cities) than the 10 dB estimated by Van Renterghem (2019). Fourth, various studies, including the underlying SIRENE survey, found that access to a quiet side may reduce annoyance (Brink et al., 2019a; de Kluienaar et al., 2011; Öhrström et al., 2006). This raises the question whether access to a quiet side and/or residential green have competing, complementary or even synergistic effects on annoyance. Indeed, access to a quiet side does not make access to green obsolete (Gidlöf-Gunnarsson and Öhrström, 2007). However, their mutual effects are still to be explored. Finally, the focus of our study was on the role of residential green as a modifier for transportation noise annoyance. Besides, vegetation may also affect (mostly reduce) noise exposure as well as reduce air pollution (Klingberg et al., 2017; Mueller et al., 2020), and also improve the urban climate (Richards et al., 2020). These additional beneficial effects for public health, however, were not in the scope of this study.

### 4.3. Outlook

While the present study, using a wide range of “green” metrics on a national scale, disclosed a wealth of results on the effects of residential green on transportation noise annoyance, open questions naturally remain. Future research in this field could focus on (i) studying additional green metrics on a national scale, such as tree cover density, alternative viewshed analyses (based, e.g., on Google Street View), 3D vegetation models, and specific types of vegetation or green spaces (e.g., forest vs. grassland), (ii) the use of green spaces for physical activity, recreation or social exchange, and its effect on annoyance, (iii) the mutual effects of having access to a quiet side vs. to residential green on annoyance, (iv) the effects of green on aircraft noise annoyance in other, non-Swiss settings to confirm our findings, (v) effects of seasonal variation in green metrics such as NDVI on annoyance, and (vi) a more detailed, dynamic noise exposure modelling to improve predictive power, accounting for exposure at home, at work and in green spaces, and the time spent in these locations.

### 5. Conclusions

Residential green was found to be associated with reduced road traffic and railway noise annoyance. Accessible green spaces and visible vegetation from home seem particularly important in cities, while the same applies to quiet green spaces in rural areas. In contrast, residential green was strongly linked to increased aircraft noise annoyance. Further studies to confirm this finding and to better understand the underlying mechanisms would be desirable. Overall, our study emphasizes that the effects of residential green go beyond a mere reduction of the noise exposure. Provision of residential green should be fostered in city planning, particularly in rapidly growing urban areas, to preserve or (re-)create visual and acoustic qualities in densely populated areas.

### 6. Authors' contributions

BS, JW study concept and design; MB provision of annoyance survey data; DV advice on and contribution to green metrics; FS processing of green metrics and link with survey data; BS data and statistical analysis; BS, MB, DV, JW data interpretation; BS write and revise draft of manuscript; all review and comment on manuscript.

### Declaration of Competing Interest

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

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### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2020.105885>.

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