Residential urban greenspace and hypertension: a comparative study in two European cities.

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Abstract

Background: Living in green areas has been associated with several health benefits; however, the available evidence on such benefits for hypertension is still limited. This study aimed to investigate and compare the association between residential exposure to greenspace and hypertension in Barcelona, Spain and Brussels, Belgium.

Methods: This cross-sectional study was based on data from the 2016 Barcelona Health Interview Survey (HIS) (n=3,400) and the 2013 Belgian HIS (n=2,335). Both surveys were harmonized in terms of outcomes, confounders and exposure assessment. Residential exposure to greenspace was characterized as 1) surrounding greenspace (normalized difference vegetation index (NDVI) and modified soil-adjusted vegetation index 2 (MSAVI2)) across buffers of 100m, 300m, and 500m; 2) surrounding green space across 300m and 500m buffers; and 3) Euclidean distance to the nearest green space. Our outcome was self-reported hypertension. We developed logistic regression models to evaluate the city-specific association between each greenspace measure and hypertension, adjusting for relevant covariates.

Results: One interquartile range (IQR) increase in residential distance to the nearest green space was associated with higher risk of hypertension in Barcelona [odds ratio (OR): 1.15; 95%CI 1.03-1.29 (IQR: 262.2)], but not in Brussels [OR: 0.95; 95%CI 0.77-1.17 (IQR: 215.2)]. Stratified analyses suggested stronger associations in older participants (≥ 65 years) for both cities. Findings for residential surrounding green space and greenspace were not conclusive. However, in Brussels, we found protective associations in older participants for both residential surrounding greenspace metrics [NDVI 300m buffer OR: 0.51; 95%CI 0.32-0.81 (IQR: 0.21) and MSAVI2 300m buffer OR: 0.51; 95%CI 0.32-0.83 (IQR: 0.18)]. We did not find any indication for the modification of our evaluated associations by sex and education level.

Conclusion: Our study suggests that living closer to greenspace could be associated with lower risk of hypertension, particularly in older age. Future research is needed to replicate our findings in other settings and shed light on potential underlying mechanism(s).

Keywords: natural environment, green space, health, urban areas, high blood pressure

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1 Introduction

The last few decades have been marked by shifting population patterns including vast migration from rural to urban areas in combination with extensive population growth. As a result of this rapid urbanization worldwide, already more than half of the world's population resides in urban areas where recent projections only expect urban population to continue to increase (Eurostat, 2016). Urban areas are generally characterized by high levels of air pollution, noise and heat, usually in combination with little available green space (i.e. public or private patches of land surface which are partly or entirely covered by grass, trees or other types of vegetation (Aerts et al., 2020)) (Nieuwenhuijsen, 2016).

Cardiovascular conditions are the leading noncommunicable diseases and the number one cause of mortality worldwide (Mendis et al., 2011; W.H.O., 2019). Hypertension is considered to be a major contributing risk factor in the aetiology of cardiovascular disease, attributing to nearly 50% of all cardiovascular deaths (W.H.O., 2013). In addition to hypertension and metabolic risk factors (e.g. dyslipidaemia and hyperglycaemia), sociodemographic and lifestyle characteristics (e.g. physical activity and smoking and drinking habits) as well as genetic predisposition have been well documented to contribute to the pathogenesis of cardiovascular diseases (W.H.O., 2013). However, the incidence of these conditions cannot be entirely explained by these risk factors only. Increasing evidence recognizes the role of environmental risk factors (e.g. air pollution and noise) in the pathogenesis of these conditions (W.H.O., 2017).

While exposure to urban-related environmental hazards including air pollution and noise has been associated with increased risk of hypertension (van Kempen et al., 2018; Yang et al., 2018; Dzhambov and Dimitrova, 2018; Nieuwenhuijsen, 2018; Zhang et al., 2019; Yang et al., 2019a; Li et al., 2020), exposure to greenspace could potentially reduce the risk of hypertension through enhancing physical activity, reducing stress, stimulating social interaction, and mitigating exposure to air pollution and noise (Brown et al., 2016; Lane et al., 2017; Bijnens et al., 2017; Dzhambov et al., 2018; Jia et al., 2018; Yang et al., 2019b). Despite the current context of increasing urbanization as well as the growing burden of cardiovascular disease, the available evidence is still limited and inconsistent (Brown et al., 2016; Lane et al., 2017; Bijnens et al., 2017; Dzhambov et al., 2018; Jia et al., 2018; Yang et al., 2019b; Xiao et al., 2020; Estes Jr et al., 2009; Paquet et al., 2014; Jendrossek et al., 2017; Tamosiunas et al., 2014; Grazuleviciene et al., 2014; Picavet et al., 2016; Groenewegen et al., 2018; Moreira et al., 2020; Plans et al., 2019). While a number of studies have suggested that higher levels of residential surrounding greenspace (i.e. satellite-based) are associated with lower risk of hypertension (Brown et al., 2016; Lane et al., 2017; Bijnens et al., 2017; Dzhambov et al., 2018; Jia et al., 2018; Yang et al., 2019b; Xiao et al., 2020), others did not report any association (Estes Jr et al., 2009; Paquet et al., 2014; Jendrossek et al., 2017). Furthermore, a small number of studies using different metrics to identify residential exposure to greenspace such as residential distance to green space (Tamosiunas et al., 2014; Grazuleviciene et al., 2014) and surrounding green space (i.e. land cover-based) (Picavet et al., 2016; Groenewegen et al.,

2018; Moreira et al., 2020; Plans et al., 2019), did not observe any association with hypertension. Moreover, only a few of these studies (Dzhambov et al., 2018; Yang et al., 2019b; Moreira et al., 2020; Xiao et al., 2020) employed various greenspace metrics, allowing to explore variability in associations with hypertension and different characteristics of greenspace. The heterogeneity in the available evidence on the association between residential exposure to greenspace and hypertension could be due to methodological differences (i.e. study design, exposure assessment, and statistical methodology) (Twohig-Bennett and Jones, 2018) or to variations in study settings (e.g. population susceptibility, culture/lifestyle, diet, climate and vegetation type/coverage). One way to disentangle these sources of heterogeneity could be by conducting comparative studies, where harmonized methodology is applied across different settings. As such, the aim of this study was to evaluate and to compare the association between residential exposure to greenspace and hypertension in two cities: Barcelona, Spain and Brussels, Belgium, in southern and central Europe, respectively.

2 Methods

2.1 Study setting

Barcelona is the second largest city of Spain and is situated along the North-eastern coastline of the Iberian Peninsula. The city has a population of about 1.6 million inhabitants residing in an area of 101.4km^2, being among the most populous urban areas in Europe (16,000/km^2). Barcelona is characterized by a Mediterranean climate, with yearly mean temperatures ranging from 15.1°C-21.2°C, an average precipitation of 571.9 mm and marked by dry summers and mild, wet winters. Mediterranean vegetation predominantly consists of evergreen trees and shrubs. The available public green per inhabitant in Barcelona consists of 3.87m^2 (Maes et al., 2019). Brussels is the capital of Belgium and is located in the north-central part of the country. The city has an oceanic climate (yearly mean temperatures between 6.9°C-14.2°C, average precipitation 852.4 mm, both mild summers and winters, and its main vegetation type is deciduous plants), with on average 15.02m^2 public green available per capita (Maes et al., 2019) and counts approximately 1.2 million inhabitants distributed across 161.4km^2 (7,384/km^2).

2.2 Study design

This cross-sectional study was based on data from the most recent available Barcelona Health Interview Survey (HIS) 2016 and the Belgian HIS 2013. Both surveys contained a wide range of questions on health status, health-related behaviors and sociodemographic variables. The survey data were constructed and collected according to the WHO guidelines on Harmonizing Methods and Instruments for Health Interview Surveys, allowing for international comparability (De Bruin et al., 1996).

For the Barcelona HIS, participants aged 15 years and older were recruited using a randomized population-based sampling approach, to equally represent all residents living in each of the ten districts of Barcelona (Bartoll et al., 2018). Data collection was conducted through face-to-face interviews applying the Computer-Assisted Personal Interviewing (CAPI) system

(Lavrakas, 2008) for the 4,000 recruited participants. The individual response rate for incumbents and first substitutes was 56.6%. Non-participants were replaced by randomly selected individuals with identical characteristics: same district, sex and age. The organization of the Barcelona HIS was in agreement with the Law of 23/1998 on Statistics of Catalonia regarding the fulfilment of statistical confidentiality (Bartoll et al., 2018).

The data for Brussels was derived from the Belgian HIS (http://www.healthsurvey.be). The survey is conducted every three to five years and is held among a representative sample of the Belgian population (n=10,000). A multistage clustered sampling design was applied for the recruitment of participants involving geographical stratification (regions and provinces), a selection of a cluster of municipalities within each stratum, of households within each cluster and of participants within each household (methodological details are described elsewhere (Demarest et al., 2013)). Data was collected through both a face-to-face (CAPI) interview, conducted with all individuals and a self-administered questionnaire for questions regarding more sensitive topics in individuals aged 15 years or older. Contrary to the Barcelona HIS, not all participants within the surveyed household completed all modules of the questionnaire due to unavailability or age restrictions of the selected household members (WIV-ISP, 2019). This resulted in reduced complete data available mainly for the health-related behavioral information. The overall household response rate for 2013 was 57%. To tackle non-response, matched substitution was applied by replacing non-participating households with households from the same sampling cluster. For the purpose of our study, we selected only individuals residing in the Brussels-Capital Region resulting in a sample size of approximately 3,000 participants. The research protocol for the Belgian HIS was approved by an ethical committee and the Belgian Privacy Commission in line with the Privacy Act of 8 December 1992, ensuring data confidentiality (WIV-ISP, 2019). We harmonized both the Barcelona and Brussels HIS data without integrating the databases into one.

2.3 Study population

This study was based on all individuals aged 18 and older who participated in the Barcelona or Brussels HIS. We excluded participants with age < 18 years (14.1% for Barcelona and 24.8% for Brussels HIS), missing or incomplete residential address (0.9% Barcelona and 4.4% Brussels) or missing outcome information (0.4% Barcelona and 0.7% Brussels). The sample eligible for analysis consisted of 3,400 adults for Barcelona and 2,335 for Brussels.

2.4 Exposure assessment

Residential exposure to greenspace was characterized using three different indicators: 1) residential surrounding greenspace and 2) residential surrounding green space as indicators of outdoor vegetation level at the living environment and 3) residential distance to the nearest green space as a proxy for access to green spaces (W.H.O., 2016). The exposure data was linked to the participants' geocoded residential address at the time of the survey. The exposure assessment was carried out using the same methodology for both cities in extracting and assigning the exposure data. Exposure assessment was done using ArcGIS (version 10) and R (version

3.4.0) (R Core Team, 2019; RStudio Team, 2019) (packages: gdalUtils (Greenberg and Mattiuzzi, 2015), raster (Hijmans, 2016), rgdal (Bivand et al., 2017)).

2.4.1 Residential surrounding greenspace

We characterized two satellite-based vegetation indices to define surrounding greenspace around the residential address; the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) and the Modified Soil-adjusted Vegetation Index 2 (MSAVI2) (Huete, 1988; Qi et al., 1994a,b). Atmospherically corrected satellite imagery for both vegetation indices was derived from the same Landsat 8 images at a spatial resolution of 30m x 30m (Gorelick et al., 2017). We selected cloud-free images during the months April-September (i.e. period of maximum vegetation in both study areas) for the year corresponding to the available HIS in each city. An algorithm was run to select the maximum (i.e. greenest) value pixels for the given period, producing composite images reflecting the study area at the peak of the growing season, regardless of the phenological cycle (Markevych et al., 2017). Further information on the retrieval of the satellite imagery can be found in the supplement (S1).

NDVI is widely used as an indicator of greenspace and is derived based on the difference of land surface reflectance of the incoming sunlight, obtained as the ratio of visible (red) and near infrared (NIR) light bands (Tucker, 1979). MSAVI2 is an alternative vegetation index using the same red and NIR bands in addition to a soil brightness correction factor, which is particularly of interest for study areas with a low degree of vegetation (e.g. deserts, prairies, and urban areas) (Qi et al., 1994b). Both NDVI and MSAVI2 values range between -1 and +1, where higher positive values indicate higher photosynthetically active vegetation. Negative values indicate water surfaces and were set to zero (Klompmaker et al., 2018). We estimated residential surrounding greenspace as the averages of separately NDVI and MSAVI2 across circular Euclidean buffers of 100m, 300m, and 500m (Dadvand et al., 2016) around the residential address resulting in 2 (indices) x 3 (buffers), i.e. 6 measures for each participant.

2.4.2 Residential surrounding green space

Residential surrounding green space were characterized using the Urban Atlas (2012) land use maps (EEA, 2019), available for both cities with a minimum spatial resolution of 0.25ha. Green spaces were identified according to the following land use classes: green urban areas (14100), sports and leisure facilities (14200), arable land (21000), permanent crops (22000), pastures (23000), complex and mixed cultivation patterns (24000), forests (31000) and herbaceous vegetation associations (32000) (EEA, 2019). We calculated the total surface of green spaces (m^2) for buffers of 300m and 500m around the residential address.

2.4.3 Residential distance to nearest green space

Residential distance to nearest green space was defined using the same Urban Atlas (2012) (EEA, 2019) land use classes as described in section

2.4.2. We calculated the Euclidean distance in meters from the participants' residential address to the nearest green space.

2.5 Outcome variable

Self-reported data on hypertension was used as the outcome of our study. Both surveys evaluated if the participant suffered from hypertension (yes vs no) by including the following question: "are you suffering, or have you suffered from hypertension?". For the participants in Brussels the question additionally included a time component by referring to "the past 12 months".

2.6 Covariate data

Both surveys collected individual data on sociodemographic variables and indicators on health-related behaviors. Demographic characteristics included age, sex, and country of birth (country of study vs foreign country). We used education level (no/primary education, secondary education or higher education) as an indicator of socioeconomic position (SEP) at individual level, and unemployment and illiteracy rate by census tract as the indicators of SEP at area level. These area level SEP indicators were derived from the census closest to the year of the HIS under study (2011 for both Barcelona and Brussels). Available health-related behavioral factors included smoking status (current, former or never) and consumption of alcohol in the last 12 months (yes vs no). Body mass index (BMI) was estimated by dividing self-reported body weight (in kilograms) by height (in meters) squared (kg/m^2).

2.7 Main analyses

Descriptive and inferential analyses were carried out for both cities separately. To account for missing covariates in both samples (4.9% Barcelona and 53.2% Brussels), we applied Multiple Imputation by Chained Equations (MICE). For Brussels, the presence of missing covariates was partly driven by the sampling strategy as described above (see section 2.2 study design) and affected mainly the health-related behavioral covariates (i.e. smoking and alcohol consumption). We carried out 25 multiple imputations with each 10 cycles of iterations. We developed city-specific weighted and stratified binary logistic regression models with hypertension as the outcome and each indicator of residential exposure to greenspace (one at a time) as the main predictor. We fitted our models with increasing covariate adjustment. The fully adjusted model included age, sex, country of birth, smoking status, alcohol use and indicators of SEP at individual (education level) and area (unemployment and illiteracy rate) levels. Covariates were selected based on previous studies on the association between residential exposure to greenspace and hypertension (Brown et al., 2016; Lane et al., 2017; Dzhambov et al., 2018; Jia et al., 2018; Yang et al., 2019b; Jendrossek et al., 2017; Tamosiunas et al., 2014; Grazuleviciene et al., 2014; Groenewegen et al., 2018), as well as data availability and harmonization potential. We explored the exposure-response relationship using GAM plots for each of the greenspace metrics, separately by city (Supplementary Figure S1). The associations were presented as odds ratios (OR) with their 95% confidence intervals (95% CI) for each interquartile range (IQR) increase in each indicator of residential exposure to greenspace

and each buffer for each city. The complexity of the different sampling designs in both surveys was considered by taking into account the provided sampling weights and the different geographical strata. Additional information on this procedure can be found in supplementary material (S2). Statistical analyses were performed with R (version 3.5.0) (R Core Team, 2019; RStudio Team, 2019) using the mgcv (Wood, 2004) mice (van Buuren and Groothuis-Oudshoorn, 2011; Robitzsch and Grund, 2019; Lumley, 2019a; Grund et al., 2019) and survey packages (Lumley, 2019b, 2004).

2.8 Sensitivity analyses

First, we evaluated the robustness of our findings by repeating the main analyses using the subset of participants without any missing value on covariates (i.e. complete case analysis). Second, we expanded the current outcome definition of self-reported hypertension by combining it with self-reported use of hypertension medication. Information on self-reported use of hypertension medication did not fully meet harmonization criteria in both surveys. Therefore, we did not use this outcome definition for our main analyses. For Barcelona, the use of hypertension medication was reported as a specific category. In the absence of a designated category for hypertension medication for Brussels, different medication groups related to hypertension were combined (i.e. antithrombotics, diuretics, beta blockers, calcium channel blockers or agents acting on the renin-angiotensin system). Last, we further adjusted our main model (separately and combined) for civil status (cohabiting/married or not), employment status (employed or not) and census tract-level percentage of foreign population.

2.9 Further analyses

2.9.1 Effect modification by age, sex, and education level

To explore potential effect modification, we evaluated the statistical significance of multiplicative interactions between each greenspace measure and age (< 65 years and ≥ 65 years), sex and education level (no/primary education, secondary education or higher education) by comparing the goodness of fit of the models with and without interaction term, using the likelihood-ratio test (LRT) with p-value $\leq$ 0.05. We then stratified our main analyses based on age, sex, and education level based on aforementioned categories. We reported the associations per IQR increase for each green indicator and stratum separately.

2.9.2 Role of BMI

We further adjusted our main models BMI, to explore whether such an adjustment could change our association estimates. In addition, we performed mediation analyses based on the difference-method (Imai et al., 2010) by using the mediation package (Tingley et al., 2014) in R statistical software to evaluate the potentially mediatory role of BMI in the association of greenspace exposure with hypertension. We obtained the proportion mediated and its 95% Quasi-Bayesian confidence intervals (95% CI) by drawing 10,000 Monte Carlo simulations. Mediation analysis was performed only when the observed association between the indicator of greenspace exposure and hypertension was statistically significant in our main model.

3 Results

3.1 Study population and residential greenspace

The sample characteristics of the HIS participants are described in Table 1. The median (IQR) age of participants in Barcelona was higher than in Brussels. In both cities, a bit more than half of the HIS participants were women. The prevalence of hypertension higher in participants in Barcelona compared to those in Brussels. The share of foreign-born individuals was larger in Brussels than in Barcelona. As expected, levels of surrounding green spaces and greenspace were higher in Brussels (Figure 1). Similarly, the median distance to nearest green space was lower in Brussels (Table 1 and Supplementary Figure S2). Pair-wise correlations between residential surrounding green space and residential surrounding greenspace ranged from 0.34 to 0.66 (Supplementary Table S1 and Table S2). Strong correlations were observed between the measures for NDVI and MSAVI2 as well as between the different buffer sizes for both surrounding green space and greenspace with values ranging between 0.70 and 0.99 and 0.86 and 0.99 for Barcelona and Brussels, respectively (Supplementary Table S1 and Table S2).

3.2 Association between residential exposure to greenspace and hypertension

We did not observe any statistically significant association between hypertension and residential surrounding green spaces and greenspace in either city (Table 2 and Supplementary Tables S3-S4 with incremental covariate adjustment). Fully adjusted odds ratios were generally close to one for participants in both Barcelona and Brussels. For residential distance to nearest green space, we found a higher risk of hypertension was associated with longer residential distance to nearest green spaces for participants from Barcelona (OR: 1.15, 95% CI 1.03-1.29 for one IQR increase in distance, Table 2). A similar association could not be observed for Brussels.

Sensitivity analyses limiting the study sample to participants with no missing covariate data (i.e. complete case analysis), did not change our results notably (Supplementary Tables S5-S6). The results for the models with an alternative definition of hypertension were similar to the main models (Supplementary Table S5-S6). Alternative regression models including a different set of sociodemographic indicators (one at the time and combined) were generally consistent with results of the main analyses (Supplementary Tables S5-S6).

After confounder adjustment of our analyses for BMI, the estimated association for residential distance to nearest green space in Barcelona became slightly weaker (OR: 1.12, 95% CI 1.00-1.26, p-value: 0.06) and became marginally statistically significant in Barcelona (Supplementary Table S7). Mediation analyses were carried out only for residential distance to nearest green space in Barcelona since only this association was statistically significant. We observed that about one-fifth of this associated could be mediated by BMI (0.221 95%CI 0.220-0.222).

3.3 Effect modification by age, sex and education level

Stratified analyses for age, sex and education level are presented for all greenspace indicators in Figure 2 (300m buffer) and Supplementary Tables S8-S10 (all buffer sizes). We observed indications for effect modification by age for distance to nearest green space in Barcelona (LRT p-value: 0.05) with suggestions for a stronger association in older participants (OR: 1.27, 95% CI 1.06-1.52). Furthermore, for Brussels significant LRT p-values were suggestive for a potential effect modification by age for both indicators of surrounding greenspace (i.e. NDVI and MSAVI2). The observed ORs were consistently significant for all buffer sizes in older Brussels adults (Figure 2 and Tables S8-S10). The strongest relation was observed in the 300m buffer with an OR of 0.51 for both NDVI (95% CI 0.32-0.81) and MSAVI2 (95% CI 0.32-0.83).

In both cities, age-stratified analyses suggested stronger protective associations between residential exposure to greenspace and hypertension for participants of older age. In addition, effect modification patterns by age seemed to be most pronounced in Brussels although most estimates did not reach statistical significance. No clear evidence for effect modification by sex or education level was observed in any of the cities. Neither could clear trends or patterns be established regarding magnitude and direction of the effect sizes in the stratified analyses.

4 Discussion

To our knowledge, this is the first study that evaluated the association between hypertension and different metrics of residential exposure to greenspace using a cross-country harmonized approach. We observed that living farther away from the nearest green space was associated with higher risk of hypertension in Barcelona, but not in Brussels. For Barcelona, we found some indications for modification of this association by age, suggesting a potentially stronger beneficial association in older participants. We did not find any association for residential surrounding green space or greenspace and hypertension in any of the cities. However, stratified analyses suggested a protective relationship between residential surrounding greenspace and hypertension in older participants in Brussels. Further adjusting for BMI attenuated the association between residential distance to nearest green space and hypertension in Barcelona.

4.1 Interpretation of the results in light of prior studies

In general, comparison of our findings with other studies is challenging given the limited body of evidence and large methodological and contextual heterogeneity between the different available studies, as was recently stated in a review by Twohig-Bennett and Jones (2018). One of the primary aims of this comparative study was to minimize methodological sources of heterogeneity in the relationship between residential exposure to greenspace and hypertension so that the role of contextual setting could be disentangled in such heterogeneity. In our study sample we observed that the proportion available greenspace on average was lower in Barcelona compared to Brussels. Additionally, in terms of variation of residential greenspace

between both cities, we found larger variations of available greenspace in the city of Brussels.

We observed a protective association between residential distance to nearest green space and hypertension in the city of Barcelona. Two prior observational studies from Kaunas, Lithuania, undertaken in pregnant women (n=3416; 20-45 y/o) and adults (n=5112; 45-72 y/o), using a similar measure for greenspace did not find any relationship with hypertension (Tamosiunas et al., 2014; Grazuleviciene et al., 2014). In addition, for Barcelona we found indications for stronger associations with residential distance to nearest green space in older age. To our knowledge, our study is the first to report an association between hypertension and residential distance to nearest green space.

With regards to residential surrounding greenspace, while the majority of the previous studies have reported that such an exposure is associated with a lower risk of hypertension (Brown et al., 2016; Lane et al., 2017; Bijnens et al., 2017; Dzhambov et al., 2018; Jia et al., 2018; Yang et al., 2019b), our study did not find any association, similar to a few other studies (Estes Jr et al., 2009; Paquet et al., 2014; Jendrossek et al., 2017). However, in our stratified analyses we observed associations in older adults in Brussels. Our evidence for effect modification by age is contrary to previous similar studies. Two European studies (Dzhambov et al., 2018; Jendrossek et al., 2017) found no effect modification by age, while two other studies conducted in China (Jia et al., 2018; Yang et al., 2019b) identified the strongest effect in the younger population (40-59 and 18-64 years, respectively). Other comparable research did not assess effect modification by age (Brown et al., 2016; Lane et al., 2017; Bijnens et al., 2017; Estes Jr et al., 2009; Paquet et al., 2014). In line with previous findings (Picavet et al., 2016; Groenewegen et al., 2018; Moreira et al., 2020; Plans et al., 2019), we did not detect any association for residential surrounding green space and hypertension in either city under study. In brief, from the three greenspace indicators that we evaluated, in Barcelona we only found an association for residential distance to the nearest green space. We considered the possibility that this could be a null finding given the absence of a statistically significant association in the unadjusted model. However, we believe this finding is plausible given its robustness in the large number of performed sensitivity analyses. One possible explanation for these results might be the homogeneity of the outdoor residential environment (i.e. lack of urban green space) for the participants in Barcelona. In Brussels, where there was larger variation and generally higher levels of residential exposure to greenspace, we detected associations with residential surrounding greenspace and hypertension among the older participants only. Additionally, other factors specific to the contextual setting across both study areas, such as topographic characteristics and features of the urban fabric might partly contribute to the explanation of the differential results between both cities.

4.2 Potential underlying mechanisms

Several mechanisms in the pathway between green and health have been hypothesized including stress reduction and recovery, higher levels of physical activity, promotion of social cohesion and reduced exposure to air pollution and noise, which are potentially important in relation with the risk of hypertension in urban populations (W.H.O., 2013; Brown et al., 2016; Lane et

al., 2017; Bijnens et al., 2017). In our study, only measures for BMI were available in a harmonized framework. Further adjustment of our main model for BMI slightly attenuated the association between residential distance to nearest green space and hypertension. Additionally, we observed suggestions for the potential mediation of the relationship between hypertension and residential exposure to greenspace by high BMI (i.e. overweight/obesity). This finding is in line with one similar study that assessed the mediating role of BMI in the relationship between residential exposure to greenspace and hypertension (Yang et al., 2019b).

4.3 Strengths and limitations

One of the main limitations of our study was that the outcome variable used in our study was self-reported and may have been subjected to recall bias. For participants in Brussels, recall bias might be smaller since the outcome definition referred to the past one-year prevalence. In addition, hypertension usually occurs without symptoms, where potentially many individuals are left undiagnosed (W.H.O., 2013). A recent systematic review on epidemiological studies evaluating the validity of self-reported hypertension as compared to confirmed clinical diagnosis concluded that in the majority of studies a considerable share of the patients is not identified when using self-reported hypertension (Goncalves et al., 2018). Results of our sensitivity analyses applying an approximation of self-reported hypertension medication use combined with self-reported hypertension indicated larger risk estimates of hypertension in relation to residential exposure to greenspace in the Barcelona sample. Consequently, the prevalence of hypertension might have been underestimated, resulting in reduced statistical power. Our study was further limited by lack of comparable and harmonizable information regarding important health-related indicators in the relationship with hypertension such as, salt-intake, pre-existing comorbidities and family medical history of hypertension, which could have modified our observed associations. Next, due to its cross-sectional design, we could not establish causal relationships, nor could we rule out presence of self-selection bias. Additionally, we performed mediation analysis, which in consequence might not be theoretically justified given the probable differential causal sequence of our mediator (VanderWeele, 2015). Another consequence of the study design is that no information on residential history was available, which might have potentially led to exposure misclassification (Markevych et al., 2017; Helbich, 2018). Our study was further limited by the assessment of only quantity and availability of greenspaces in vicinity of the participants' homes. Due to privacy restrictions, land use classes could not be linked separately to participants to study association of hypertension with different types of green spaces. In addition, information on quality or usability of these greenspaces was not available, which could have influenced the actual use of these spaces by our participants and hence our study outcome. A final limitation of this study is the substantial number of missing values for covariates on health-related behavior in the Belgian HIS. To a great extent, missingness of these covariates was generated by the survey design since not all household members completed the same survey modules depending on their availability at the time of the home visit of the HIS interviewers. Furthermore, in both cities, participants with a lower education level were more likely to have missing values. However, we tried to address this limitation by imputing missing covariates in both surveys. In addition, results using complete case

analysis were similar. Notwithstanding these limitations, this study had a number of strengths. To capture different aspects of urban green areas, this study used various objective measures of residential exposure to greenspace. The use of both land use and satellite-based data could be complementary (Markevych et al., 2017). In addition, the use of two distinct vegetation indices could have been informative since it is still unclear whether associations with health are different depending on the index used. Both indices were strongly correlated but their underlying spatial distribution differed. While NDVI is most commonly used in observational studies and allows for comparability among similar research, MSAVI2 seeks to overcome one of the main limitations of NDVI when applied to areas with a low degree of vegetation. Finally, we evaluated the association between hypertension and residential exposure to greenspace in a cross-country harmonized approach, comparing two cities with contextual differences in terms of physical (climate, size, vegetation patterns) and human (population distribution and composition, built environment) geographical structures.

5 Conclusion

This study assessed and compared the association of residential exposure to greenspace with hypertension between Barcelona and Brussels. Our findings contribute to the current heterogeneous body of evidence by using a cross-country harmonized approach, enabling us to disentangle the contextual sources of heterogeneity from its methodological sources. For Barcelona, we observed a protective association between residential distance to nearest green space and risk of hypertension, especially in older age. No association was observed for residential surrounding greenspace in Barcelona. For Brussels, we found a protective association between residential surrounding greenspace and hypertension in older participants only. Further work is needed to study our evaluated associations in other settings by applying a longitudinal design based on repeated measures of blood pressure and different indicators of greenspace exposure across different settings while trying to shed light on the potential mechanisms underlying these associations.

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Supplementary material

Residential urban greenspace and hypertension: a comparative study in two European cities.

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S1. Additional information on the exposure assessment: collection of the NDVI and MSAVI2 satellite imagery.

We used two remote sensing vegetation indices to define surrounding greenspace around the residential address; the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) and the Modified Soil-adjusted Vegetation Index 2 (MSAVI2) (Huete, 1988; Qi et al., 1994a,b). Atmospherically corrected satellite imagery for both vegetation indices was derived from Landsat 8 at a spatial resolution of 30 m x 30 m (Gorelick et al., 2017). We selected cloud-free images during the months April-September (i.e. period of maximum vegetation in both study areas) for the year corresponding to the available HIS in each city (i.e. 2016 for Barcelona and 2013 for Brussels). An algorithm was run to select the maximum (i.e. greenest) value pixels for the given period, producing composite images reflecting the study area at the peak of the growing season, regardless of the phenological cycle. The satellite imagery used in our study were retrieved using Google Earth Engine (GEE) (Gorelick et al., 2017; Markevych et al., 2017). Scripts and procedure applied in obtaining these images has been documented below for each vegetation index separately (S1.1 for NDVI and S1.2 for MSAVI2).

S1.1. Script used to retrieve NDVI satellite images trough GEE (example for Barcelona).

1) The area for which the satellite image will be created is first defined by creating a variable which contains the coordinates of a polygon covering the city under study. For both Barcelona and Brussels polygons have been created and stored in a variable named geometry (example below applies for Barcelona).

```
var geometry = ee.FeatureCollection(
        [ee.Feature(
            ee.Geometry.Polygon(
                [[[2.560925562286343, 41.47282199818569],
          [1.823468286895718, 41.47385095570615],
          [1.845440943145718, 41.06303626742759]]]),
            {
              "system:index": "0"
            })]);
```

2) Cloud-free images of atmospherically corrected surface reflectance Landsat 8 images are selected for the year corresponding to the Health Interview Survey for each city (2016 Barcelona and 2013 Brussels) during the months April until September.

```
var imagecol = ee.ImageCollection("LANDSAT/LC08/C01/T1_SR")
  .filterDate('2016-01-01', '2016-12-31')
  .filter(ee.Filter.calendarRange(4, 9, 'month'))
  .filterBounds(geometry)
  .sort('CLOUD_COVER', false)
```

3) A function is created to calculate the NDVI based on the visible (red) and near infrared (NIR) light bands.

```
var getNDVI = function(image) {
  var ndvi = image.normalizedDifference(['B5', 'B4']).rename('NDVI');
  return image.addBands(ndvi);
};
```

4) The NDVI is calculated based on the previously selected image collection.

```
var withNDVI = imagecol.map(getNDVI);
```

5) The maximum (i.e. greenest) value pixels for the selected image collection is being calculated in order to retrieve the image at the peak of the growing season.

```
var greenest = withNDVI.qualityMosaic('NDVI');
var NDVI = greenest.select('NDVI');
```

6) The image is being cropped to the selected study area previously defined.

```
var NDVI = NDVI.clipToCollection(geometry)
```

7) Visual inspection of the image and export for further processing (buffer calculation and exposure assessment)

```
var visParams = {min: -1, max: 1, palette: ['blue', 'white', 'green']};
Map.addLayer(NDVI, visParams, 'NDVI');
 Export.image.toDrive({
  image: NDVI,
```

```
  description: 'maxNDVI_l8_SR_2016_BCN',
  scale: 30,
  maxPixels:1e13,
  region: geometry
});
```

S1.2. Script used to retrieve MSAVI2 satellite images trough GEE (example for Barcelona).

1) The area for which the satellite image will be created is first defined by creating a variable which contains the coordinates of a polygon covering the city under study. For both Barcelona and Brussels polygons have been created and stored in a variable named geometry. The code below applies for the area of Barcelona, adjustments have been made accordingly when retrieving the images for the study area of Brussels.

```
var geometry = ee.FeatureCollection(
        [ee.Feature(
            ee.Geometry.Polygon(
                [[[2.560925562286343, 41.47282199818569],
              [1.823468286895718, 41.47385095570615],
              [1.845440943145718, 41.06303626742759]]]),
              {
                "system:index": "0"
              })]);
```

2) Cloud-free images of atmospherically corrected surface reflectance Landsat 8 images are selected for the year corresponding to the Health Interview Survey for each city (2016 Barcelona and 2013 Brussels) during the months April until September. The selected dates below apply for the study period of Barcelona, adjustment regarding the year of the Landsat 8 collection have been made when collecting the images for the Brussels study period for 2013.

```
var imagecol = ee.ImageCollection("LANDSAT/LC08/C01/T1_SR")
  .filterDate('2016-01-01', '2016-12-31')
  .filter(ee.Filter.calendarRange(4, 9, 'month'))
  .filterBounds(geometry)
  .sort('CLOUD_COVER', false)
```

3) A function is created to calculate the MSAVI2 based on the visible (red) and near infrared (NIR) light bands and a soil brightness correction factor.

```
var getMSAVI = function(image) {
  var msavi = image.select('B5').multiply(2).add(1)
  .subtract(image.select('B5').multiply(2).add(1).pow(2)
    .subtract(image.select('B5').subtract(image.select('B4')).multiply(8)).sqrt()
  ).divide(2).rename('MSAVI');
  return image.addBands(msavi)
};
```

4) The MSAVI2 is calculated based on the previously selected image collection.

```
var withMSAVI = imagecol.map(getMSAVI);
```

5) The maximum (i.e. greenest) value pixels for the selected image collection is being calculated in order to retrieve the image at the peak of the growing season.

```
var greenest = withMSAVI.qualityMosaic('MSAVI');
var MSAVI = greenest.select('MSAVI');
```

6) The image is being cropped to the selected study area previously defined.

```
var MSAVI = MSAVI.clipToCollection(geometry)
```

7) Visual inspection of the image and export for further processing (buffer calculation and exposure assessment)

```
var visParams = {min: -1, max: 1, palette: ['blue', 'white', 'green']};
Map.addLayer(MSAVI, visParams, 'MSAVI');
Export.image.toDrive({
  image: MSAVI,
  description: 'maxMSAVI2_l8_SR_2016_BCN',
  scale: 30,
  maxPixels:1e13,
  region: geometry
});
```

S2. Additional information on the sampling weights and the application in the statistical modelling.

Both the Barcelona Health Interview Survey (HIS) and the Brussels HIS data were collected employing a multistage sampling design approach. Participants of the Barcelona HIS were recruited using a randomised population-based sampling approach, to equally represent all residents living in each of the ten districts of Barcelona (Bartoll et al., 2018). Regarding the Brussels HIS, a multistage clustered sampling design was applied for the recruitment of participants involving geographical stratification (regions and provinces), a selection of a cluster of municipalities within each stratum, of households within each cluster and of participants within each household (methodological details are described elsewhere (Demarest et al., 2013)). In order to allow for valid statistical inferences in our study, we accounted for the complexity of the different sampling designs by adjusting for the provided sampling weights in both surveys. We performed our analyses with R (version 3.5.0) (R Core Team, 2019; RStudio Team, 2019) using the survey package (Lumley, 2019, 2004), to support the validity of our analytical models and to avoid violation of the statistical assumption of independence of observations. The use of the survey package implies defining a *svydesign* object in which a complex survey design is being specified. In turn, this object is integrated in the logistic regression model used in this study to analyse the association between different greenspace metrics and self-reported hypertension.

S2.1 Construction of the *svydesign* object for both surveys under study

The *svydesign* object has been defined in collaboration with the institutions responsible for organizing and processing the HIS in both cities, namely Agència de Salut Pública de Barcelona for the Barcelona HIS and the Scientific Direction Epidemiology and Public Health of Sciensano for the Brussels HIS.

Svydesign object specifications	Barcelona HIS	Brussels HIS
ids	individual id	household id
strata	districts	provinces
weights	sample population weight 'PONDERA'*	sample population weight 'wfin'*
data	Barcelona HIS data	Brussels HIS data

*More information on the construction of the sample weights can be found in the

manuals of both the Barcelona HIS (Bartoll et al., 2018) and the Brussels HIS (WIV-ISP, 2019).

Table S1. Pearson (bottom left) and Spearman (top right) correlation heatmap for the different environmental exposure measures for Barcelona

		Barcelona								
		NDVI			**MSAVI2**			**Urban Atlas**		**Euclidean distance to nearest green space**
	Exposure	**100-m buffer**	**300-m buffer**	**500-m buffer**	**100-m buffer**	**300-m buffer**	**500-m buffer**	**300-m buffer**	**500-m buffer**	
NDVI	**100-m buffer**	1	0.78	0.66	0.99	0.79	0.67	0.34	0.35	-0.37
	300-m buffer	0.82	1	0.92	0.78	0.99	0.92	0.53	0.54	-0.51
	500-m buffer	0.71	0.94	1	0.67	0.92	0.99	0.53	0.62	-0.53
MSAVI2	**100-m buffer**	0.99	0.82	0.71	1	0.79	0.67	0.34	0.35	-0.37
	300-m buffer	0.82	0.99	0.93	0.82	1	0.92	0.51	0.53	-0.50
	500-m buffer	0.71	0.93	0.99	0.71	0.94	1	0.52	0.60	-0.52
Urban Atlas	**300-m buffer**	0.38	0.56	0.54	0.37	0.53	0.51	1	0.81	-0.91
	500-m buffer	0.37	0.57	0.64	0.36	0.54	0.61	0.86	1	-0.77
Euclidean distance to nearest green space		-0.34	-0.45	-0.47	-0.35	-0.45	-0.47	-0.54	-0.54	1

Table S2. Pearson (bottom left) and Spearman (top right) correlation heatmap for the different environmental exposure measures for Brussels

		Brussels								
		NDVI			**MSAVI2**			**Urban Atlas**		**Euclidean distance to nearest green space**
	Exposure	**100-m buffer**	**300-m buffer**	**500-m buffer**	**100-m buffer**	**300-m buffer**	**500-m buffer**	**300-m buffer**	**500-m buffer**	
NDVI	**100-m buffer**	1	0.91	0.87	0.99	0.91	0.87	0.47	0.56	-0.40
	300-m buffer	0.91	1	0.98	0.91	0.99	0.98	0.54	0.65	-0.43
	500-m buffer	0.86	0.98	1	0.87	0.98	0.99	0.52	0.68	-0.39
MSAVI2	**100-m buffer**	0.99	0.91	0.87	1	0.91	0.87	0.47	0.56	-0.40
	300-m buffer	0.91	0.99	0.97	0.91	1	0.98	0.53	0.64	-0.42
	500-m buffer	0.86	0.97	0.99	0.87	0.98	1	0.51	0.67	-0.38
Urban Atlas	**300-m buffer**	0.46	0.54	0.51	0.45	0.51	0.49	1	0.84	-0.89
	500-m buffer	0.53	0.64	0.67	0.52	0.62	0.64	0.84	1	-0.71
Euclidean distance to nearest green space		-0.39	-0.42	-0.40	-0.38	-0.41	-0.39	-0.63	-0.57	1

Table S3. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace with incremental adjustments for Barcelona.

	Barcelona (n=3400)					
	Unadjusted	Adjusted[a]	Adjusted[b]	Adjusted[c]	Adjusted[d]	Adjusted[e]
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Surrounding greenspace (NDVI)						
100-m buffer	1.07 (0.97-1.18)	1.02 (0.90-1.15)	1.02 (0.90-1.15)	1.02 (0.90-1.15)	1.02 (0.90-1.15)	1.01 (0.89-1.14)
300-m buffer	**1.11 (1.00-1.22)***	1.05 (0.94-1.18)	1.05 (0.94-1.18)	1.06 (0.94-1.18)	1.05 (0.93-1.17)	1.04 (0.92-1.16)
500-m buffer	1.10 (0.99-1.22)	1.07 (0.95-1.20)	1.07 (0.95-1.20)	1.07 (0.95-1.21)	1.06 (0.94-1.19)	1.05 (0.92-1.18)
Surrounding greenspace (MSAVI2)						
100-m buffer	1.08 (0.97-1.20)	1.02 (0.90-1.15)	1.02 (0.90-1.15)	1.02 (0.90-1.16)	1.02 (0.90-1.15)	1.01 (0.89-1.15)
300-m buffer	**1.12 (1.01-1.24)***	1.06 (0.94-1.19)	1.05 (0.94-1.19)	1.06 (0.94-1.19)	1.05 (0.93-1.18)	1.04 (0.92-1.17)
500-m buffer	1.11 (0.99-1.24)	1.07 (0.94-1.21)	1.07 (0.94-1.21)	1.07 (0.94-1.21)	1.06 (0.93-1.20)	1.04 (0.92-1.18)
Surrounding green spaces (Urban Atlas)						
300-m buffer	1.03 (0.95-1.11)	1.00 (0.92-1.10)	1.00 (0.92-1.09)	1.00 (0.92-1.10)	0.99 (0.91-1.09)	0.99 (0.90-1.08)
500-m buffer	1.08 (1.00-1.18)	1.09 (0.99-1.19)	1.08 (0.98-1.19)	1.09 (0.99-1.20)	1.07 (0.96-1.18)	1.06 (0.96-1.17)
Euclidean distance to nearest green space (Urban Atlas)	1.04 (0.95-1.15)	1.11 (0.99-1.24)	1.12 (1.00-1.25)	1.11 (1.00-1.25)	**1.14 (1.01-1.27)***	**1.15 (1.03-1.29)***

* p-value < 0.05.

[a]Adjusted for age

[b]Adjusted for age, sex, country of birth

[c]Adjusted for age, sex, country of birth, smoking status, alcohol use

[d]Adjusted for age, sex, country of birth, smoking status, alcohol use, education level

[e]Adjusted for age, sex, country of birth, smoking status, alcohol use, education level, unemployment rate and illiteracy rate

Table S4. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace with incremental adjustments for Brussels.

	Brussels (n=2335)					
	Unadjusted	Adjusted[a]	Adjusted[b]	Adjusted[c]	Adjusted[d]	Adjusted[e]
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Surrounding greenspace (NDVI)						
100-m buffer	**1.24 (1.01-1.52)***	0.90 (0.72-1.12)	0.96 (0.76-1.22)	0.97 (0.76-1.24)	0.99 (0.77-1.27)	1.04 (0.81-1.35)
300-m buffer	1.16 (0.95-1.43)	0.84 (0.67-1.07)	0.92 (0.72-1.18)	0.92 (0.71-1.19)	0.94 (0.72-1.22)	1.00 (0.76-1.33)
500-m buffer	1.15 (0.94-1.41)	0.84 (0.67-1.07)	0.92 (0.72-1.18)	0.92 (0.71-1.19)	0.94 (0.72-1.22)	1.01 (0.76-1.34)
Surrounding greenspace (MSAVI2)						
100-m buffer	**1.24 (1.01-1.53)***	0.90 (0.72-1.12)	0.97 (0.76-1.23)	0.98 (0.76-1.25)	1.00 (0.78-1.28)	1.06 (0.81-1.37)
300-m buffer	1.17 (0.95-1.44)	0.85 (0.68-1.07)	0.93 (0.72-1.19)	0.93 (0.72-1.20)	0.95 (0.73-1.23)	1.01 (0.76-1.34)
500-m buffer	1.16 (0.94-1.43)	0.84 (0.67-1.07)	0.92 (0.72-1.19)	0.92 (0.71-1.20)	0.94 (0.72-1.23)	1.02 (0.76-1.36)
Surrounding green spaces (Urban Atlas)						
300-m buffer	1.03 (0.90-1.17)	0.96 (0.83-1.12)	1.00 (0.86-1.16)	0.99 (0.85-1.15)	0.99 (0.85-1.15)	1.01 (0.86-1.17)
500-m buffer	1.06 (0.89-1.25)	0.98 (0.82-1.19)	1.03 (0.86-1.24)	1.02 (0.85-1.23)	1.03 (0.86-1.24)	1.07 (0.88-1.29)
Euclidean distance to nearest green space (Urban Atlas)	0.91 (0.74-1.12)	0.98 (0.79-1.20)	0.95 (0.77-1.18)	0.96 (0.78-1.18)	0.96 (0.78-1.18)	0.95 (0.77-1.17)

* p-value < 0.05.

[a]Adjusted for age

[b]Adjusted for age, sex, country of birth

[c]Adjusted for age, sex, country of birth, smoking status, alcohol use

[d]Adjusted for age, sex, country of birth, smoking status, alcohol use, education level

[e]Adjusted for age, sex, country of birth, smoking status, alcohol use, education level, unemployment rate and illiteracy rate

Table S5. Sensitivity analysis adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace for Barcelona.

	Barcelona						
	Main model multiple imputation[a]	Main model complete cases[b]	Main model alternative outcome[c]	Main model alternative sociodemographic indicator (civil status)[d1]	Main model alternative sociodemographic indicators (employment status)[d2]	Main model alternative sociodemographic indicators (foreign population)[d3]	Main model alternative sociodemographic indicators (combined)[d4]
	(n=3400)	(n=3231)	(n=3399)	(n=3400)	(n=3400)	(n=3400)	(n=3400)
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Surrounding greenspace (NDVI)							
100-m buffer	1.01 (0.89-1.14)	1.05 (0.90-1.15)	1.01 (0.90-1.14)	1.01 (0.89-1.14)	1.01 (0.90-1.14)	1.03 (0.91-1.16)	1.03 (0.91-1.16)
300-m buffer	1.04 (0.92-1.16)	1.03 (0.92-1.17)	1.00 (0.89-1.13)	1.03 (0.92-1.16)	1.04 (0.92-1.17)	1.05 (0.94-1.18)	1.05 (0.93-1.18)
500-m buffer	1.05 (0.92-1.18)	1.05 (0.92-1.19)	1.00 (0.88-1.13)	1.04 (0.92-1.18)	1.05 (0.93-1.19)	1.06 (0.94-1.20)	1.07 (0.94-1.21)
Surrounding greenspace (MSAVI2)							
100-m buffer	1.01 (0.89-1.15)	1.01 (0.89-1.16)	1.01 (0.89-1.15)	1.01 (0.88-1.14)	1.01 (0.89-1.15)	1.03 (0.90-1.17)	1.03 (0.90-1.17)
300-m buffer	1.04 (0.92-1.17)	1.03 (0.91-1.17)	1.00 (0.88-1.13)	1.03 (0.91-1.17)	1.04 (0.92-1.17)	1.06 (0.93-1.19)	1.05 (0.93-1.19)

500-m buffer	1.04 (0.92-1.18)	1.05 (0.92-1.19)	0.99 (0.87-1.13)	1.04 (0.91-1.18)	1.05 (0.92-1.19)	1.06 (0.93-1.21)	1.07 (0.94-1.21)
Surrounding green spaces (Urban Atlas)							
300-m buffer	0.99 (0.90-1.08)	0.97 (0.88-1.08)	0.96 (0.87-1.05)	0.98 (0.90-1.08)	0.99 (0.90-1.08)	0.99(0.91-1.09)	0.99 (0.90-1.09)
500-m buffer	1.06 (0.96-1.17)	1.06 (0.95-1.18)	1.03 (0.93-1.15)	1.06 (0.96-1.17)	1.06 (0.96-1.18)	1.07 (0.96-1.18)	1.07 (0.97-1.18)
Euclidean distance to nearest green space (Urban Atlas)	**1.15 (1.03-1.29)***	**1.16 (1.03-1.30)***	**1.19 (1.06-1.33)***	**1.15 (1.03-1.29)***	**1.15 (1.02-1.28)***	**1.13 (1.01-1.27)***	**1.13 (1.01-1.27)***

* p-value < 0.05

[a] Main model multiple imputation: Adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

[b] Main model complete cases: Adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

[c] Alternative outcome: Combined outcome self-reported hypertension with cardiovascular medication use and adjusted for the abovementioned variables.

[d] Main model multiple imputation[a] additionally adjusted for civil status[1] , employment status[2], area-level percentage of foreign population[3] both separately and combined[4].

Table S6. Sensitivity analysis adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace for Brussels.

	Brussels						
	Main model multiple imputation[a]	Main model complete cases[b]	Main model alternative outcome[c]	Main model alternative sociodemographic indicator (civil status)[d1]	Main model alternative sociodemographic indicators (employment status)[d2]	Main model alternative sociodemographic indicators (foreign population)[d3]	Main model alternative sociodemographic indicators (combined)[d4]
	(n=2335)	(n=1092)	(n=2330)	(n=2335)	(n=2335)	(n=2335)	(n=2335)
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Surrounding greenspace (NDVI)							
100-m buffer	1.04 (0.81-1.35)	0.99 (0.70-1.39)	1.23 (0.96-1.56)	1.04 (0.81-1.35)	1.02 (0.79-1.32)	1.01 (0.74-1.39)	1.02 (0.74-1.41)
300-m buffer	1.00 (0.76-1.33)	0.86 (0.61-1.23)	1.16 (0.90-1.51)	1.00 (0.75-1.32)	0.98 (0.73-1.30)	0.93 (0.63-1.37)	0.93 (0.63-1.37)
500-m buffer	1.01 (0.76-1.34)	0.85 (0.59-1.22)	1.15 (0.88-1.50)	1.01 (0.76-1.34)	0.99 (0.74-1.32)	0.94 (0.64-1.39)	0.95 (0.64-1.40)
Surrounding greenspace (MSAVI2)							
100-m buffer	1.06 (0.81-1.37)	0.99 (0.70-1.40)	1.23 (0.96-1.58)	1.05 (0.81-1.37)	1.03 (0.79-1.34)	1.03 (0.74-1.44)	1.04 (0.74-1.45)
300-m buffer	1.01 (0.76-1.34)	0.87 (0.60-1.24)	1.17 (0.90-1.52)	1.01 (0.76-1.34)	0.98 (0.74-1.31)	0.94 (0.63-1.40)	0.94 (0.63-1.40)

500-m buffer	1.02 (0.76-1.36)	0.85 (0.60-1.22)	1.15 (0.87-1.52)	1.01 (0.75-1.36)	0.99 (0.74-1.33)	0.95 (0.63-1.43)	0.95 (0.63-1.43)
Surrounding green spaces (Urban Atlas)							
300-m buffer	1.01 (0.86-1.17)	0.89 (0.71-1.11)	1.07 (0.94-1.22)	1.01 (0.86-1.17)	0.98 (0.84-1.15)	0.99 (0.84-1.16)	0.98 (0.83-1.16)
500-m buffer	1.07 (0.88-1.29)	0.89 (0.68-1.15)	1.13 (0.97-1.32)	1.06 (0.88-1.28)	1.04 (0.86-1.25)	1.05 (0.86-1.28)	1.04 (0.85-1.28)
Euclidean distance to nearest green space (Urban Atlas)	0.95 (0.77-1.17)	1.08 (0.84-1.38)	0.88 (0.72-1.06)	0.95 (0.77-1.17)	0.98 (0.81-1.20)	0.96 (0.78-1.19)	0.98 (0.80-1.20)

* p-value < 0.05

[a] Main model multiple imputation: Adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

[b] Main model complete cases: Adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

[c] Alternative outcome: Combined outcome self-reported hypertension with cardiovascular medication use and adjusted for the abovementioned variables.

[d] Main model multiple imputation[a] additionally adjusted for civil status[1] , employment status[2], area-level percentage of foreign population[3] both separately and combined[4].

Table S7. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace after adjustment for BMI.

	Barcelona (n=3400)		Brussels (n=2335)	
	Adjusted[a]	Adjusted[a] + BMI	Adjusted[a]	Adjusted[a] + BMI
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Surrounding greenspace (NDVI)				
100-m buffer	1.01 (0.89-1.14)	1.01 (0.89-1.13)	1.04 (0.81-1.35)	1.06 (0.83-1.36)
300-m buffer	1.04 (0.92-1.16)	1.03 (0.92-1.16)	1.00 (0.76-1.33)	1.00 (0.76-1.31)
500-m buffer	1.05 (0.92-1.18)	1.05 (0.93-1.18)	1.01 (0.76-1.34)	0.99 (0.75-1.30)
Surrounding greenspace (MSAVI2)				
100-m buffer	1.01 (0.89-1.15)	1.00 (0.88-1.14)	1.06 (0.81-1.37)	1.08 (0.84-1.39)
300-m buffer	1.04 (0.92-1.17)	1.03 (0.91-1.17)	1.01 (0.76-1.34)	1.01 (0.77-1.33)
500-m buffer	1.04 (0.92-1.18)	1.05 (0.92-1.19)	1.02 (0.76-1.36)	0.99 (0.75-1.32)
Surrounding green spaces (Urban Atlas)				
300-m buffer	0.99 (0.90-1.08)	0.99 (0.91-1.09)	1.01 (0.86-1.17)	0.98 (0.84-1.15)
500-m buffer	1.06 (0.96-1.17)	1.06 (0.96-1.17)	1.07 (0.88-1.29)	1.04 (0.86-1.26)
Euclidean distance to nearest green space (Urban Atlas)	**1.15 (1.03-1.29)***	1.12 (1.00-1.26)	0.95 (0.77-1.17)	0.98 (0.78-1.23)

* p-value < 0.05.

[a] Adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

Table S8. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace stratified by age.

	Barcelona				Brussels			
	Full sample (n=3400)	Age <65 years (n=2499)	Age ≥65 years (n=901)		Full sample (n=2335)	Age <65 years (n=1914)	Age ≥65 years (n=421)	
	OR (95% CI)	OR (95% CI)	OR (95% CI)	LRT p-value	OR (95% CI)	OR (95% CI)	OR (95% CI)	LRT p-value
Surrounding greenspace (NDVI)								
100-m buffer	1.01 (0.89-1.14)	1.00 (0.84-1.18)	1.00 (0.85-1.19)	0.81	1.04 (0.81-1.35)	1.25 (0.93-1.96)	**0.65 (0.42-1.00)***	**0.01**
300-m buffer	1.04 (0.92-1.16)	1.03 (0.87-1.20)	1.01 (0.85-1.20)	0.61	1.00 (0.76-1.33)	1.28 (0.91-1.79)	**0.51 (0.32-0.81)***	**0.01**
500-m buffer	1.05 (0.92-1.18)	1.05 (0.89-1.24)	1.00 (0.83-1.20)	0.47	1.01 (0.76-1.34)	1.24 (0.87-1.77)	**0.56 (0.35-0.91)***	**0.01**
Surrounding greenspace (MSAVI2)								
100-m buffer	1.01 (0.89-1.15)	1.00 (0.83-1.19)	1.00 (0.84-1.19)	0.80	1.06 (0.81-1.37)	1.27 (0.93-1.74)	**0.65 (0.42-1.01)***	**0.01**
300-m buffer	1.04 (0.92-1.17)	1.03 (0.87-1.22)	1.00 (0.84-1.19)	0.56	1.01 (0.76-1.34)	1.29 (0.91-1.82)	**0.51 (0.32-0.83)***	**0.01**
500-m buffer	1.04 (0.92-1.18)	1.05 (0.89-1.25)	0.99 (0.82-1.19)	0.44	1.02 (0.76-1.36)	1.24 (0.86-1.80)	**0.56 (0.35-0.92)***	**0.01**
Surrounding green spaces (Urban Atlas)								
300-m buffer	0.99 (0.90-1.08)	0.93 (0.81-1.06)	1.03 (0.90-1.17)	0.64	1.01 (0.86-1.17)	1.04 (0.87-1.24)	0.84 (0.61-1.15)	0.06
500-m buffer	1.06 (0.96-1.17)	1.04 (0.91-1.20)	1.04 (0.90-1.22)	0.90	1.07 (0.88-1.29)	1.12 (0.88-1.41)	0.85 (0.59-1.22)	**0.04**
Euclidean distance to nearest green	**1.15 (1.03-1.29)***	1.07 (0.91-1.25)	**1.27 (1.06-1.52)***	**0.05**	0.95 (0.77-1.17)	0.80 (0.62-1.04)	1.35 (0.98-1.85)	**0.02**

space (Urban Atlas)

* p-value < 0.05.

Note: All models are adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

Table S9. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace stratified by sex.

	Barcelona				Brussels			
	Full sample (n=3400)	Men (n=1590)	Women (n=1810)		Full sample (n=2335)	Men (n=1082)	Women (n=1253)	
	OR (95% CI)	OR (95% CI)	OR (95% CI)	LRT p-value	OR (95% CI)	OR (95% CI)	OR (95% CI)	LRT p-value
Surrounding greenspace (NDVI)								
100-m buffer	1.01 (0.89-1.14)	0.97 (0.82-1.17)	1.04 (0.88-1.23)	0.59	1.04 (0.81-1.35)	0.99 (0.67-1.46)	1.11 (0.82-1.52)	0.74
300-m buffer	1.04 (0.92-1.16)	1.03 (0.87-1.21)	1.04 (0.88-1.23)	0.75	1.00 (0.76-1.33)	0.95 (0.61-1.46)	1.08 (0.77-1.52)	0.69
500-m buffer	1.05 (0.92-1.18)	1.05 (0.88-1.25)	1.04 (0.87-1.24)	0.81	1.01 (0.76-1.34)	1.02 (0.65-1.59)	1.04 (0.74-1.46)	0.40
Surrounding greenspace (MSAVI2)								
100-m buffer	1.01 (0.89-1.15)	0.99 (0.82-1.19)	1.02 (0.86-1.22)	0.76	1.06 (0.81-1.37)	1.00 (0.67-1.49)	1.14 (0.83-1.55)	0.77
300-m buffer	1.04 (0.92-1.17)	1.04 (0.88-1.24)	1.02 (0.86-1.22)	0.98	1.01 (0.76-1.34)	0.95 (0.61-1.47)	1.10 (0.79-1.55)	0.73
500-m buffer	1.04 (0.92-1.18)	1.07 (0.89-1.28)	1.02 (0.84-1.22)	0.97	1.02 (0.76-1.36)	1.01 (0.64-1.62)	1.06 (0.75-1.50)	0.43
Surrounding green spaces (Urban Atlas)								
300-m buffer	0.99 (0.90-1.08)	0.89 (0.77-1.02)	1.08 (0.95-1.22)	**0.02**	1.01 (0.86-1.17)	0.99 (0.79-1.24)	1.00 (0.81-1.23)	0.99
500-m buffer	1.06 (0.96-1.17)	0.97 (0.84-1.12)	1.15 (1.00-1.33)	**0.03**	1.07 (0.88-1.29)	1.11 (0.83-1.47)	1.02 (0.80-1.30)	0.51
Euclidean distance to nearest green	**1.15 (1.03-1.29)***	1.13 (0.95-1.34)	**1.18 (1.01-1.39)***	0.91	0.95 (0.77-1.17)	0.92 (0.65-1.30)	1.00 (0.79-1.26)	0.56

space (Urban Atlas)

* p-value < 0.05.

Note: All models are adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

Table S10. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace stratified by education level.

	Barcelona					Brussels				
	Full sample (n=3400)	No/primary education (n≈1241.76)[a]	Secondary education (n≈916.6)[a]	Higher education (n≈1241.64)[a]		Full sample (n=2335)	No/primary education (n≈308.28)[a]	Secondary education (n≈1003.4)[a]	Higher education (n≈1023.32)[a]	
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	LRT p-value	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	LRT p-value
Surrounding greenspace (NDVI)										
100-m buffer	1.01 (0.89-1.14)	1.01 (0.85-1.20)	0.96 (0.75-1.24)	0.98 (0.76-1.27)	0.97	1.04 (0.81-1.35)	1.27 (0.74-2.17)	1.33 (0.91-1.93)	0.73 (0.49-1.06)	0.18
300-m buffer	1.04 (0.92-1.16)	1.04 (0.88-1.22)	0.94 (0.73-1.22)	1.03 (0.80-1.31)	0.81	1.00 (0.76-1.33)	1.08 (0.61-1.92)	1.39 (0.91-1.93)	0.70 (0.46-1.07)	0.21
500-m buffer	1.05 (0.92-1.18)	1.03 (0.87-1.22)	0.99 (0.75-1.30)	1.04 (0.80-1.35)	0.93	1.01 (0.76-1.34)	1.06 (0.59-1.91)	1.44 (0.94-2.21)	0.72 (0.47-1.10)	0.23
Surrounding greenspace (MSAVI2)										
100-m buffer	1.01 (0.89-1.15)	1.01 (0.84-1.21)	0.97 (0.74-1.26)	0.97 (0.74-1.26)	0.97	1.06 (0.81-1.37)	1.30 (0.77-2.20)	1.33 (0.90-1.94)	0.75 (0.51-1.11)	0.23
300-m buffer	1.04 (0.92-1.17)	1.04 (0.88-1.24)	0.95 (0.72-1.24)	1.01 (0.79-1.31)	0.83	1.01 (0.76-1.34)	1.12 (0.64-1.96)	1.36 (0.89-2.08)	0.73 (0.48-1.11)	0.28
500-m buffer	1.04 (0.92-1.18)	1.03 (0.86-1.23)	0.98 (0.74-1.30)	1.03 (0.79-1.35)	0.93	1.02 (0.76-1.36)	1.10 (0.61-1.98)	1.44 (0.93-2.23)	0.73 (0.47-1.13)	0.28
Surrounding green spaces (Urban Atlas)										

300-m buffer	0.99 (0.90-1.08)	0.98 (0.87-1.10)	0.88 (0.70-1.11)	1.08 (0.90-1.31)	0.39	1.01 (0.86-1.17)	0.85 (0.60-1.22)	1.17 (0.96-1.44)	0.89 (0.67-1.18)	0.12
500-m buffer	1.06 (0.96-1.17)	1.04 (0.91-1.18)	1.06 (0.83-1.35)	1.10 (0.88-1.38)	0.98	1.07 (0.88-1.29)	0.86 (0.56-1.31)	1.26 (0.97-1.63)	0.94 (0.65-1.34)	0.17
Euclidean distance to nearest green space (Urban Atlas)	**1.15 (1.03-1.29)***	1.05 (0.89-1.25)	1.17 (0.93-1.47)	**1.29 (1.06-1.58)***	0.35	0.95 (0.77-1.17)	1.10 (0.73-1.65)	0.78 (0.57-1.06)	1.05 (0.75-1.47)	0.27

* p-value < 0.05.

Note: All models are adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

[a] Subsample totals are extracted from each city-specific multiple imputed dataset and averaged given the observed missings for education level for Barcelona and Brussels (0.2% and 11.3%, respectively).

Figure S1. Exposure-response curves and 95% confidence intervals (95% CI; grey dashed line) for the association between hypertension and different measures of greenspace. Density bars with the distribution of the different greenspace metrics are displayed on the y-axis.

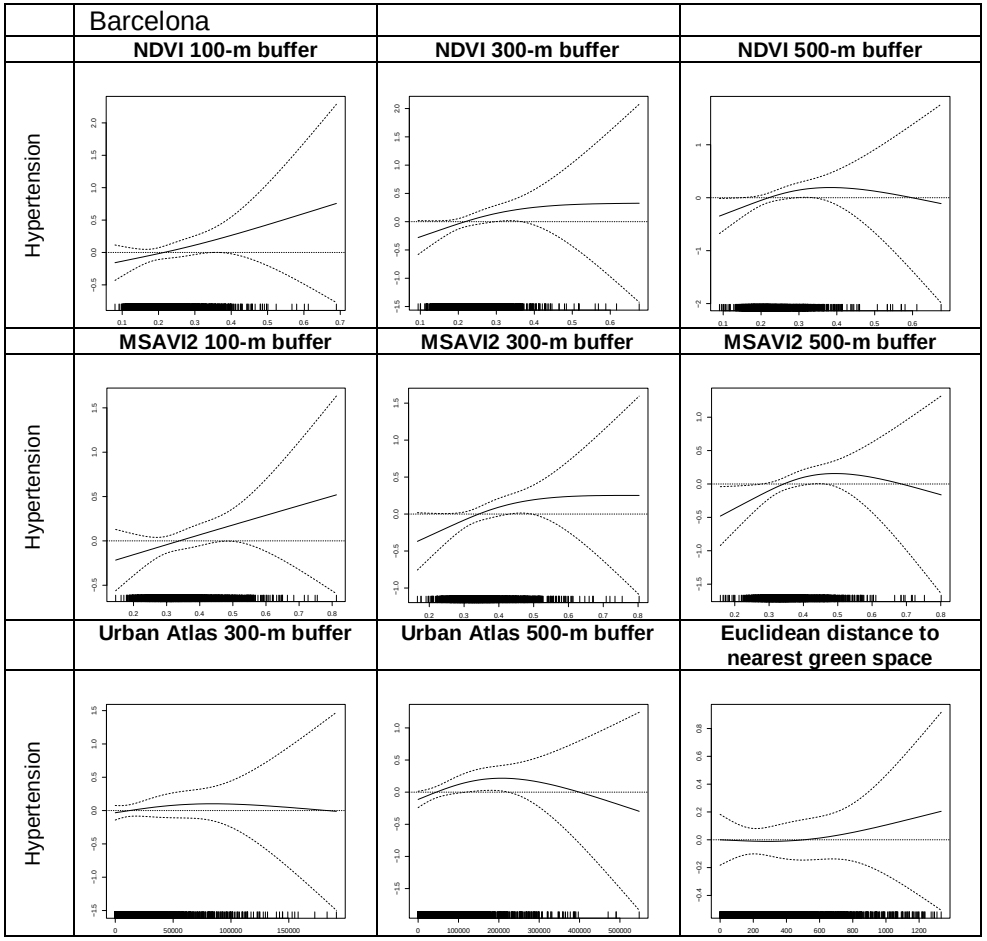


Figure S1. (Continued). Exposure-response curves and 95% confidence intervals (95% CI; grey dashed line) for the association between hypertension and different measures of greenspace. Density bars with the distribution of the different greenspace metrics are displayed on the y-axis.

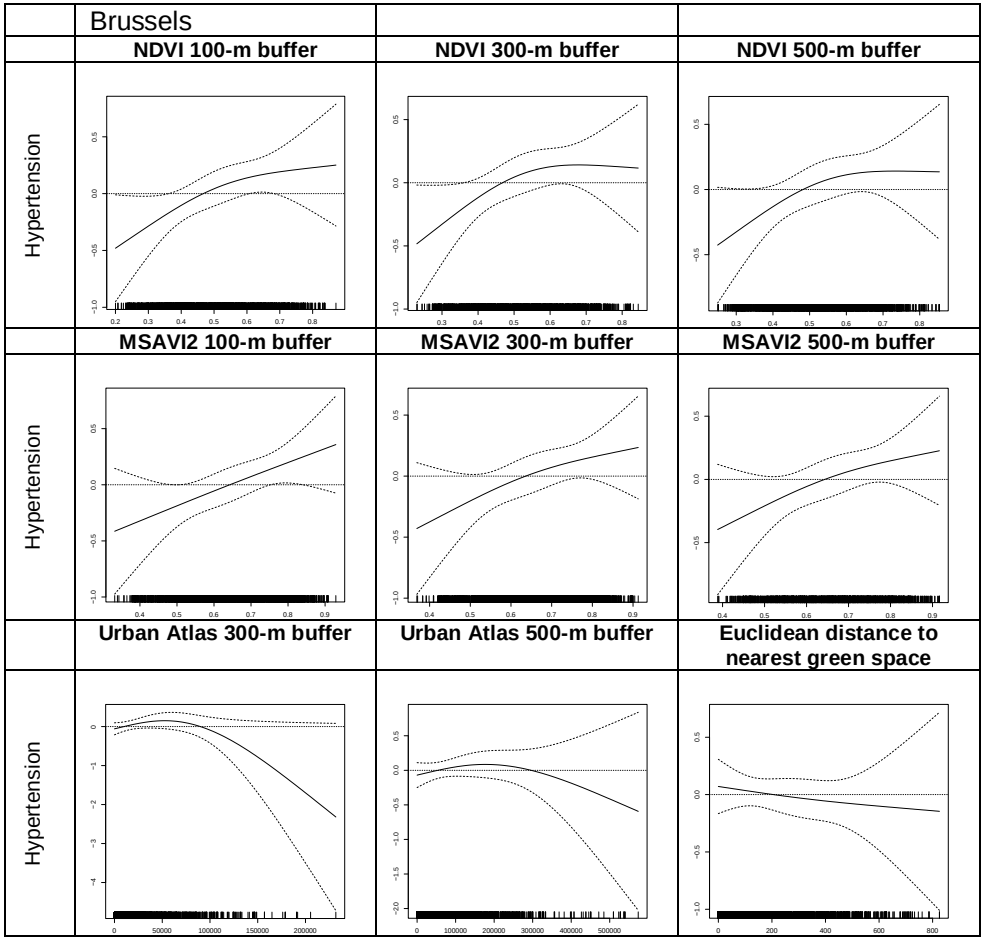
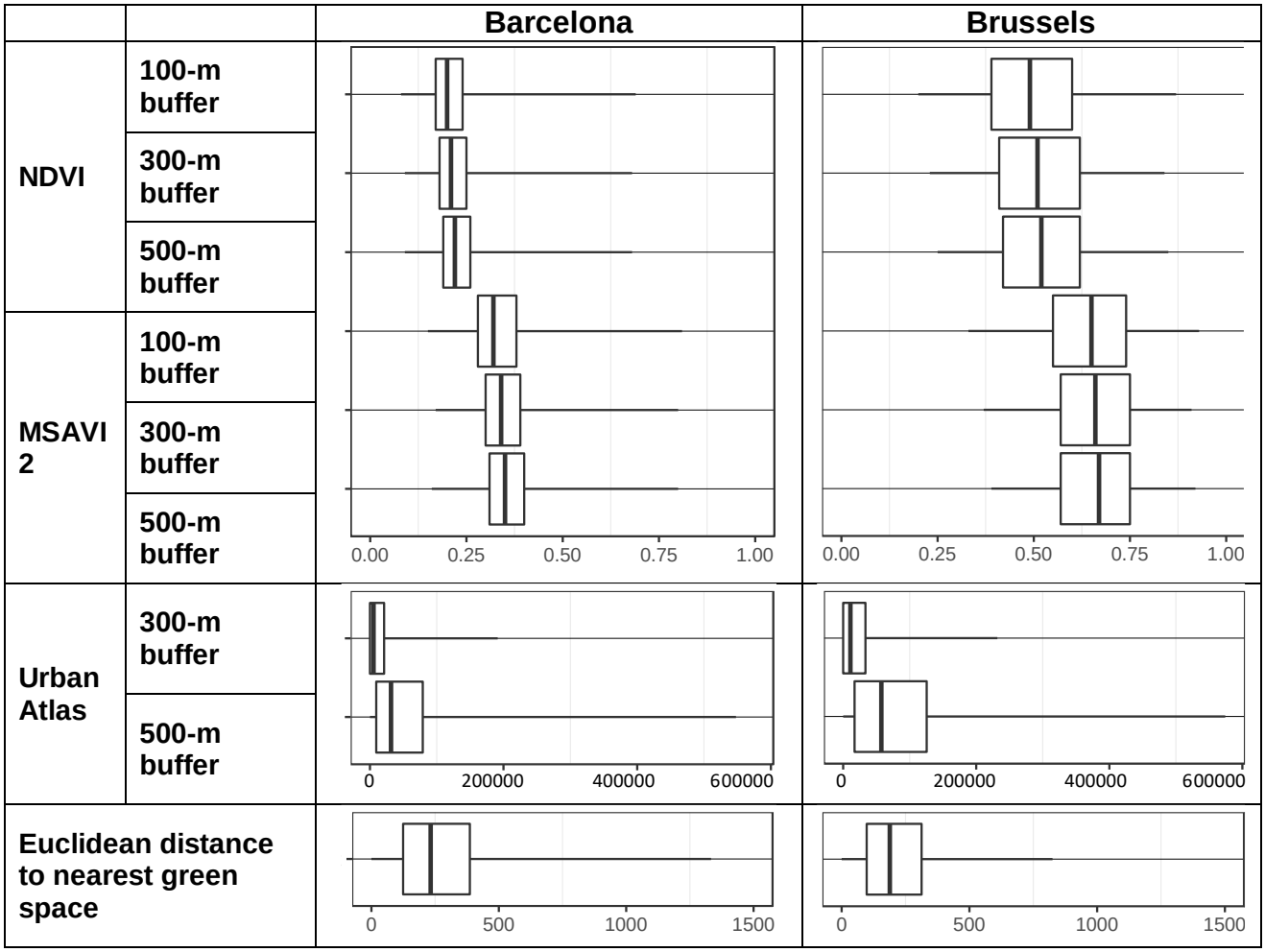


Figure S2. Boxplots with the distribution of the different greenspace measures.



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Tables and figures to be included in the main manuscript

Residential urban greenspace and hypertension: a comparative study in two European cities.

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Table 1. Characteristics of the Health Interview Survey participants by city**.**

Variable	*Barcelona HIS*	*Brussels HIS*
N total (>17 years): n	3400	2335
Age: median (IQR)	48 (31)	45 (27)
Sex: n (%)		
Men	1590 (46.8)	1082 (46.3)
Women	1810 (53.2)	1253 (53.7)
Country of birth: n (%)		
Country of study	2584 (76.0)	1187 (50.8)
Foreign	808 (23.8)	1141 (48.9)
Missing	8 (0.2)	7 (0.3)
Education level: n (%)		
No/primary education	1239 (36.4)	293 (12.5)
Secondary education	914 (26.9)	893 (38.2)
Higher education	1239 (36.4)	884 (37.9)
Missing	8 (0.2)	265 (11.3)
Smoking status: n (%)		
Current	2479 (72.9)	275 (11.8)
Former	125 (3.7)	242 (10.4)
Never	644 (18.9)	729 (31.2)
Missing	152 (4.5)	1089 (46.6)
Alcohol use (consumed in the last 12 months): n (%)		
Yes	2564 (75.4)	915 (39.2)
No	687 (20.2)	316 (13.5)
Missing	149 (4.4)	1104 (47.3)
Body mass index (BMI)		
BMI: median (IQR)	24.8 (5.45)	24.6 (5.75)
Missing: n (%)	3 (0.1)	74 (3.2)
Unemployment rate: median (IQR)	20.3 (10.9)	14.9 (12.1)
Illiteracy rate: median (IQR)	6.3 (6.4)	3.1 (3.6)
Morbidity: hypertension prevalence: n (%)	719 (21.1)	408 (17.5)
Surrounding greenspace (NDVI): median (IQR)		
100-m buffer	0.20 (0.08)	0.49 (0.20)
300-m buffer	0.21 (0.07)	0.51 (0.21)
500-m buffer	0.22 (0.07)	0.52 (0.20)
Surrounding greenspace (MSAVI2): median (IQR)		
100-m buffer	0.32 (0.10)	0.65 (0.18)
300-m buffer	0.34 (0.09)	0.66 (0.18)
500-m buffer	0.35 (0.09)	0.67 (0.18)
Surrounding green spaces in m^2 (Urban Atlas): median (IQR)		
300-m buffer	5307.8 (21174.8)	11043.5 (33461.5)
500-m buffer	31636.4 (69572.1)	57433.0 (108362.4)
Euclidean distance to nearest green space in m (Urban Atlas): median (IQR)	232.4 (262.2)	188.8 (215.2)

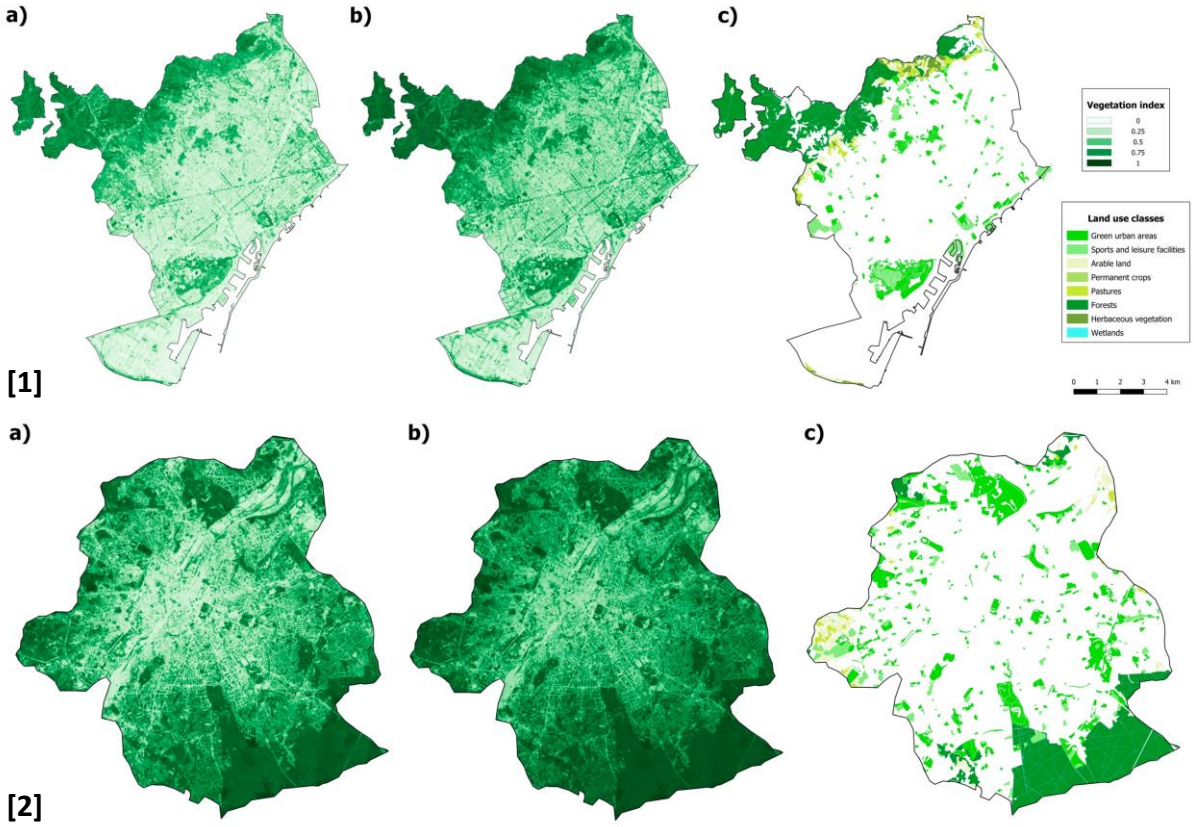
Table 2. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace.

	Barcelona (n=3400)		Brussels (n=2335)	
	Unadjusted	Adjusted[a]	Unadjusted	Adjusted[a]
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)
Surrounding greenspace (NDVI)				
100-m buffer	1.07 (0.97-1.18)	1.01 (0.89-1.14)	**1.24 (1.01-1.52)***	1.04 (0.81-1.35)
300-m buffer	**1.11 (1.00-1.22)***	1.04 (0.92-1.16)	1.16 (0.95-1.43)	1.00 (0.76-1.33)
500-m buffer	1.10 (0.99-1.22)	1.05 (0.92-1.18)	1.15 (0.94-1.41)	1.01 (0.76-1.34)
Surrounding greenspace (MSAVI2)				
100-m buffer	1.08 (0.97-1.20)	1.01 (0.89-1.15)	**1.24 (1.01-1.53**)*	1.06 (0.81-1.37)
300-m buffer	**1.12 (1.01-1.24)***	1.04 (0.92-1.17)	1.17 (0.95-1.44)	1.01 (0.76-1.34)
500-m buffer	1.11 (0.99-1.24)	1.04 (0.92-1.18)	1.16 (0.94-1.43)	1.02 (0.76-1.36)
Surrounding green spaces (Urban Atlas)				
300-m buffer	1.03 (0.95-1.11)	0.99 (0.90-1.08)	1.03 (0.90-1.17)	1.01 (0.86-1.17)
500-m buffer	1.08 (1.00-1.18)	1.06 (0.96-1.17)	1.06 (0.89-1.25)	1.07 (0.88-1.29)
Euclidean distance to nearest green space (Urban Atlas)	1.04 (0.95-1.15)	**1.15 (1.03-1.29)***	0.91 (0.74-1.12)	0.95 (0.77-1.17)

* p-value < 0.05.

[a] Adjusted for age, sex, country of birth, education level, smoking status, alcohol use, unemployment rate and illiteracy rate.

Figure 1. Maps of NDVI[1] (a), MSAVI2[2] (b), and Urban Atlas (a) for Barcelona [1] and Brussels [2]).



[1] Normalized Difference Vegetation Index
[2] Modified Soil-Adjusted Vegetation Index
Note: Both vegetation indices (NDVI and MSAVI2) were retrieved for the year corresponding to the Health Interview Survey (HIS) in each city (i.e. 2016 for Barcelona and 2013 for Brussels). Urban Atlas data was available for 2012, the year closest to the year of the HIS in either city.

Figure 2. Adjusted odds ratio (OR) and 95% confidence intervals (95% CI) of the association between hypertension and one interquartile increase (IQR) for different measures of greenspace for 300-m buffers by strata (age, sex and education level).