



Greenspace seems protective of both high and low blood pressure among residents of an Alpine valley

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ABSTRACT

Background: There is some data suggesting that residential greenspace may protect against high blood pressure in urbanized areas, but there is no evidence of effects on hypotension, in less urbanized areas, and in idiosyncratic geographic contexts such as mountain valleys.

Objectives: The current study aimed to investigate the associations between residential greenspace and blood pressure in an alpine valley in Austria.

Methods: We conducted a cross-sectional survey of a representative sample of 555 adults living in the Lower Inn Valley, Austria. Several definitions of blood pressure were employed: continuously-measured systolic (SBP) and diastolic blood pressure (DBP), doctor-diagnosed hyper- and hypotension, and high- and low blood pressure medication use. Greenspace metrics considered were: Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and tree cover as measures of surrounding greenness in circular buffers of 100 m, 300 m, 500 m, and 1000 m around the home; distance to different types of structured green space; and having a domestic garden and a balcony. Relationships were examined across different definitions of blood pressure and greenspace and evaluated for potential effect modification by demographic factors, presence of a domestic garden/balcony, adiposity, and traffic sensitivity.

Results: Higher overall greenness was associated with 30–40% lower odds of hyper/hypotension and 2–3 mm Hg lower SBP. Similar pattern was revealed for tree cover, however, associations with hypertension were less consistent across buffers, and SBP and DBP were lower only in association with greenness in the 100-m buffer. Having a domestic garden also seemed protective of high DBP. Residing near to forests, agricultural land, or urban green spaces was not related to blood pressure. Higher NDVI_{500-m} was stronger associated with lower SBP in those having a domestic garden, while the effect on DBP was stronger in overweight/obese participants.

Conclusion: These findings support the idea that greenspace should be considered as protective of both high and low blood pressure, however, underlying mechanisms remain insufficiently understood.

1. Introduction

Hypertension is a major risk factor for the development and progression of cardiovascular disease, accounting for roughly half of deaths due to ischemic heart disease and stroke worldwide (WHO, 2013). In addition to classic behavioral factors (WHO, 2013), multiple studies have demonstrated the potential of the residential environment to modify the risk of hypertension. For instance, traffic-related air pollution (Yang et al., 2018) and noise (Dzhambov and Dimitrova, 2018; Kempen et al., 2018) can promote high blood pressure via a cascade of

neuroendocrine processes, including autonomic nervous system imbalance, oxidative stress, and endothelial dysfunction (Münzel et al., 2017). However, other residential features, such as greenspace, can have a protective effect (Nieuwenhuijsen et al., 2017; Dadvand and Nieuwenhuijsen, 2019). Through the lens of Ulrich's psycho-evolutionary theory (Ulrich, 1983), engagement with nature may support normal blood pressure by shifting the vegetative nervous system balance towards parasympathetic activation and by reducing levels of stress hormones (Ulrich et al., 1991; Hartig et al., 2003; Park et al., 2010; Li et al., 2011). Green areas also lack traffic sources and, under

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certain conditions, vegetation might mitigate air pollution and noise (Markevych et al., 2017). In addition to disrupting harmful pathways, green spaces are typically characterized by high restorative quality, allowing respite from everyday stress (von Lindern et al., 2017) and motivating health-enhancing behaviors like outdoor physical activity and social interactions (Markevych et al., 2017).

Epidemiological research on the relationship between greenspace and blood pressure is gaining momentum. Residents of neighborhoods with higher greenness and those living near green spaces (i.e., “exposed” to higher greenspace) have been found to be at lower risk of hypertension (Grazuleviciene et al., 2014; Brown et al., 2016; Groenewegen et al., 2018; Jia et al., 2018) and even death due to hypertension-related causes (Vienneau et al., 2017). Greenspace might also reduce systolic and diastolic blood pressure (Markevych et al., 2014; Bijmens et al., 2017; Lane et al., 2017). Yet, findings to date are conflicting and not generalizable to all residents. For example, Jendrossek et al. (2017) did not observe a positive effect on maternal hypertension. A meta-analysis showed that residents exposed to high amounts of greenspace had -1.97 mm Hg (95% CI: -3.45 , -0.49) lower diastolic blood pressure compared with their counterparts. No significant effect was found for systolic blood pressure (-1.50 mm Hg; 95% CI: -3.43 , 0.44) and incidence of hypertension (OR = 0.99 ; 95% CI: 0.81 , 1.20) though (Twohig-Bennett and Jones, 2018).

Moreover, the epidemiologic literature on the topic has prominent gaps. For instance, earlier studies only considered greenspace as protective of high blood pressure (cf. Twohig-Bennett and Jones, 2018). However, low blood pressure is also of public health importance. Aside from diminishing health-related quality of life (i.e., causing fatigue, dizziness, headache, cold limbs, depressed mood, to name a few), hypotension is associated with falls in the elderly (McDonald et al., 2016; Hartog et al., 2017) and also independently increases incidence of adverse cardiovascular events (Ricci et al., 2015), leading to 36% increase in risk of overall mortality (Angelousi et al., 2014). That hypotension has escaped the spotlight of research may be attributed to the fact that such data are rarely available in health surveys and that the potential mechanisms linking hypotension to greenspace are poorly understood. Nevertheless, there is some evidence supporting this conjecture. Lercher et al. observed an association between traffic noise and hypotension in individuals with compromised autonomic regulation (Lercher and Widmann, 2013; Lercher et al., 2014). Another study suggested that anxiety and depression are independently associated with lower blood pressure (Hildrum et al., 2007). Thus, greenspace might decrease risk of hypotension by reducing noise level and psychological stress (cf. Markevych et al., 2017).

Another issue rarely considered is whether the effect of greenspace varies across different geographic contexts (Ruijsbroek et al., 2017). Markevych et al. (2014) looked at greenness and blood pressure in children and observed a beneficial association only in urban, but not rural, settings. In addition to urbanization, topographic features of the residential area might act as effect modifiers. For instance, steepness of the terrain in hilly areas was proposed to protect of diabetes by increasing physical activity (Villanueva et al., 2013; Fujiwara et al., 2017). No previous study has investigated the effect of greenspace in mountain valleys often characterized by temperature inversions, as well as propagation of sound waves over great distances, leading to high levels of air pollution and noise (Heimann et al., 2007). Also, some types of greenspace have been found to be more beneficial to blood pressure than others (urban vs agricultural) (Picavet et al., 2016). This may be related to differences in vegetation characteristics and its potential to reduce traffic emissions (Van Renterghem et al., 2015; Baldauf, 2017) and different usage or visual effects of agricultural fields and green areas in urban settings, where other features of the built environment may interfere with restoration (Hartig et al., 2003; Van den Berg et al., 2014). Although experts have recommended employing a set of different metrics representing different aspects of greenspace potentially relevant to different ways of understanding its effects

(Markevych et al., 2017), no previous study on blood pressure has implemented this approach (cf. Twohig-Bennett and Jones, 2018).

Based on the literature gaps outlined above, the current study aimed to investigate the associations between residential greenspace and blood pressure in the Lower Inn Valley (Unterinntal) in Austria. This area is an ideal setting for addressing limitations of earlier research: it comprises peri-urban settlements, neither strictly urban, nor rural in character; residents of those settlements are exposed to high levels of traffic noise and air pollution; at the same time, they have access to landscapes of high aesthetic quality, diverse in their function and vegetation characteristics. We examined this relationship across different definitions of blood pressure and greenspace and evaluated the effect of potential effect modifiers.

2. Material and methods

2.1. Study area and design

Data for the present study come from a comprehensive cross-sectional survey conducted in the framework of an Environmental Health Impact Assessment (fall 1998) in the Lower Inn Valley, Austria. They were never fully analyzed due to an interruption in funding and lack of manpower.

The study area extends about 40 km east of Innsbruck towards the Austrian-German border across a relatively broad valley floor and up to the foothills of the Alpine comb. (Fig. 1) The valley floor is characterized by the river Inn and two heavy traffic routes (a highway and a railway). In addition, major roads link the villages and the highway. The transportation lines follow mostly the course of the river Inn, which is the major water feature in the area. Owing to the dominance of the major traffic routes, the landscape is fragmented and settlements consist of densely populated small towns and villages with a mix of industrial, small business, touristic, and agricultural activities (Wrbka et al., 2004; von Lindern et al., 2016). Given its busy transport infrastructure combined with sensitive topography and meteorology (inversions) high levels of air pollution and traffic noise have been observed in the area (Lercher et al., 1995; Lercher and Kofler, 1996; Heimann et al., 2007). Conversely, landscapes in this part of Austria comprise natural and semi-natural biotopes and agricultural areas with high nature value (Wrbka et al., 2004); in particular, the Lower Inn Valley is situated in a region of renowned scenic beauty (von Lindern et al., 2016).

The data we used for the present re-analysis were originally intended to supplement and deepen the health information collected in a larger representative study to assess the health impact of traffic-related pollution. Interested readers can find a detailed account of the design and sampling scheme elsewhere (Lercher et al., 2014; von Lindern et al., 2016). Briefly, eligible adult participants were sampled randomly with replacement from 648 households located within a 500-m radius from around 31 sound measurement sites, approximately equally distributed across pre-defined noise map bands (35–44, 45–54, 55–64, > 64 $L_{eq,dBA}$). Potential participants were replaced when the sampling criteria (e.g., age, duration of residence) were not met due to the incompleteness or incorrectness of the sampling data base received from governmental sources. Adults who had been residing at the address for at least one year were invited to participate in the door-to-door interview. Some households were represented by more than one member. Households were visited twice, with the second visit focusing on collecting detailed health status information. 572 residents agreed to provide health data during this second visit, and of those, we only considered 555 for the present analyses, because they had both blood pressure data and residential greenspace could be successfully assigned to their home address. Comparison between participants' characteristics and census data and between participants and those who dropped out after the first visit indicated that our analytic sample was mostly representative of the population (except for a higher proportion of

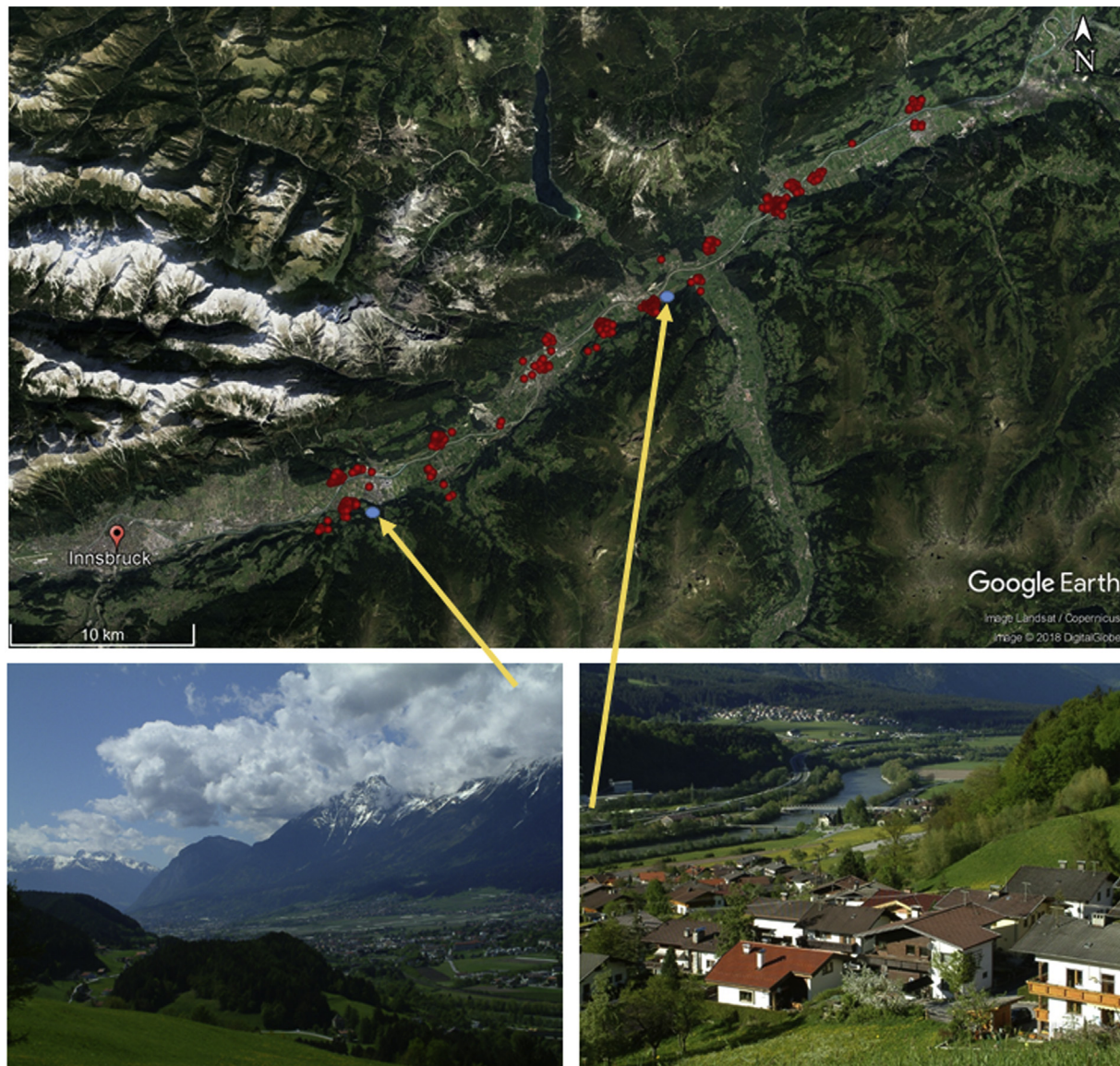


Fig. 1. Participants' home addresses (red dots) in the Lower Inn Valley, Austria – a satellite image (top panel) and eye-level photographs (bottom panels) of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

women) and there is no reason to suspect relevant self-selection (Lercher et al., 2014; von Lindern et al., 2016). Participants provided written informed consent before the interview and the anthropometric measurement protocols were completed.

2.2. Blood pressure assessment

For comparability with previous research (cf. Twohig-Bennett and Jones, 2018), several definitions of blood pressure were employed. Systolic and diastolic blood pressure readings were obtained on the right arm in a sitting position after a three minute rest. Measurements were done prior to and after the interview using a calibrated mercury sphygmomanometer with a large scale (Sysdion, Fa. F. Bosch, Jungingen, Germany). Blood pressure was assessed based on the first and fifth Korotkoff phase using a fixed deflation rate of 3 mm Hg/s. Reporting was required to 1 mm Hg to avoid digit preference. A uniform cuff-size (12 cm × 28 cm) was used. 5 to 10 days after the interview, a third and fourth reading was obtained. For the current analyses, we use the mean of these two second visit readings because we believe they better represent participants' "casual blood pressure". In addition,

participants were asked whether, during the past 12 months, they had been diagnosed by a doctor with hyper/hypotension and whether they had been taking medication against high/low blood pressure (Lercher et al., 2014). These variables provided conceptually different information and therefore were used as alternative definitions of hyper/hypotension. For example, one definition of hypertension was having been diagnosed with hypertension, and another, taking antihypertensive medication (regardless of whether a diagnosis of hypertension was reported). This way, robustness of associations across different definitions of blood pressure would increase our confidence in the effect of greenspace and its clinical relevance.

2.3. Greenspace assessment

Following expert recommendations (Markevych et al., 2017) and previous accounts of differential effects depending on how greenspace is defined (Picavet et al., 2016; Dzhambov et al., 2018a), we considered alternative metrics giving different perspectives on greenspace potentially relevant to its effects on blood pressure. Remotely-sensed vegetation indices and tree cover served as measures of surrounding

greenness, while land use/cover classes differentiated between different types of green areas.

Normalized Difference Vegetation Index (NDVI; Tucker, 1979) is commonly used as a proxy for overall vegetation level and ranges from -1 to $+1$, where positive values closer to 1 indicate high greenness (Gascon et al., 2016). It was calculated based on the difference of surface reflectance in two vegetation-informative wavelengths – visible red and near infrared light. Soil Adjusted Vegetation Index (SAVI; Huete, 1988) is an alternative vegetation index, which differs from NDVI in that it includes a correction factor in its algorithm to suppress soil pixels (Huete, 1988). For these calculations, we used a single cloud-free Landsat 5 Thematic Mapper (TM) satellite image obtained during summer (on August 10, 1998) to grasp maximum vegetation contrast (<https://earthexplorer.usgs.gov/>). Prior to calculations, we removed all water pixels from the satellite images before NDVI and SAVI assignment by using the Open Street Maps (OSM) water layer (Gascon et al., 2018; Dzhambov et al., 2018a).

Tree cover was defined as the percentage of surface covered by woody vegetation higher than 5 m. It was calculated as the annual average value for the year 2000 based on a Landsat Vegetation Continuous Fields map (Sexton et al., 2013; Markevych et al., 2016) (<http://glcf.umd.edu/data/landsatTreecover/>). NDVI, SAVI, and tree cover were calculated at a resolution of $30\text{ m} \times 30\text{ m}$ as mean values in circular buffers of 100 m, 300 m, 500 m, and 1000 m around the residential address.

Distance to different types of green spaces was calculated as a proxy for accessibility. OSM supplied data on urban green spaces, such as parks, cemeteries, allotments, and recreational grounds. Forest and agricultural land use was elicited from the CORINE 2000 land cover map at a resolution of $25\text{ m} \times 25\text{ m}$ (Annerstedt et al., 2012) (<https://land.copernicus.eu/pan-european/corine-land-cover/clc-2000/view>). Different data sources were used for different types of green spaces, because urban green spaces are small in size and are therefore not included into the CORINE 2000 dataset. To make interpretation of our results more relevant to urban planning, these variables were categorized for the main analyses, based on the data distribution: distance to urban green spaces $\leq 300\text{ m}$, 301–500 m, and $> 500\text{ m}$, and distances to forest areas and agricultural lands $\leq 100\text{ m}$, 101–300 m, and $> 300\text{ m}$.

Finally, we considered whether participants had a domestic garden (no vs yes) and a balcony (no vs yes). These may serve as resources for interaction with greenspace while at home (cf. Dahlkvist et al., 2016; Soga et al., 2017).

In line with previous studies, we considered NDVI in the 500-m buffer for the main analyses (Markevych et al., 2014; Vienneau et al., 2017; Jendrossek et al., 2017); however, we also report sensitivity analyses with the other metrics and buffers. Geographic data management and calculations were carried out using ArcGIS 10.4 Geographical Information System (GIS) (ESRI, Redlands, CA, USA).

2.4. Covariates

Factors believed to confound, modify, or mediate the health effects of greenspace (Markevych et al., 2017) and related to blood pressure (WHO, 2013) were considered in the covariate list. We also reviewed the adjustment approach of previous studies on the topic (cf. Twhig-Bennett and Jones, 2018). However, our intent was to keep the models parsimonious. The questionnaire supplied data on participant's age, sex, education (≥ 10 years vs < 10 years), home ownership (owner, co-habitation, or renting), crowding in the household (person/room ratio), smoking status (yes vs no), and family history of hypertension (yes vs no/unknown). Education, home ownership, and person/room ratio served as proxies for socioeconomic status. Euclidean distance to the nearest bluespace (water body) in the 100-m, 300-m, 500-m, and 1000-m buffers is OSM-based and was dichotomized (presence vs absence) in the analyses to facilitate interpretation and because it was grossly

skewed.

Total day-night noise exposure (L_{dn}) due to road and rail traffic was modelled according to the Austrian guidelines (ÖAL Nr. 28 + 30, ÖNORM S 5011) at a resolution of $25\text{ m} \times 25\text{ m}$ after calibration against the measurements from the 31 sampling sites (Lercher et al., 2014; von Lindern et al., 2016). Nitrogen dioxide (NO_2), one component of air pollution, served as a proxy for traffic-related air pollution and was calculated at a resolution of $100\text{ m} \times 100\text{ m}$ using an adapted Gaussian propagation model procedure considering the meteorological and topographic specifics of the study area (Lercher et al., 2014; von Lindern et al., 2016).

Mental health problems were assessed using the sum of 14 items from the General Health Questionnaire (GHQ). These items were scored on a 4-point scale and tapped anxiety and depression symptoms (von Lindern et al., 2016). Traffic-related annoyance in participant's home and its surroundings was assessed by six items asking about noise from motorways, noise from local traffic, noise from railways, vibration from railways, air pollution from traffic, and pollution from particles. These items could be answered on an 11-point response scale, and we took their mean for the analyses. In addition, we considered average sensitivity to traffic exposures (air pollution, noise, and vibration), which was assessed with three items (0 = not at all sensitive to 10 = particularly sensitive) (von Lindern et al., 2016).

Body mass index (BMI) was calculated as weight (kg) divided by height squared (m^2). Anthropometric measurements were obtained during the first visit and adhered to a standardized protocol.

2.5. Statistical analysis

Given the reasonably low proportion of missing data ($< 5\%$ on any given variable; Little's MCAR test, $p > 0.05$), missing values were imputed using the expectation-maximization algorithm (Dempster et al., 1977; Pigott, 2001). Prior to the main analyses, the relationships between NDVI_{500-m} and blood pressure variables were tested using restricted cubic splines with three knots at the 10th, 50th, and 95th percentiles (*xbrcspline* command in Stata) (Orsini, 2009) and no deviation from linearity was detected. We then employed multivariate linear regression models for continuously-measured blood pressure, and multivariate logistic regression models for hypertension diagnosis/mediation and hypotension diagnosis/medication. These models did not suffer from multicollinearity according to tolerance (< 0.2) and Variance Inflation Factor (> 5) values. Effect estimates of NDVI, SAVI, and tree cover are reported per interquartile range increase. The clustered structure of the data (i.e., participants residing in different communities) was addressed by using the Huber-Eicker-White-sandwich method to obtain a robust variance estimate that adjusts for within-cluster correlations (Rogers, 1993; Williams, 2000; Cameron and Miller, 2015).

Next, the following factors were tested as potential modifiers of the effect of NDVI_{500-m} on systolic/diastolic blood pressure: sex, age, education, having a domestic garden, having a balcony, BMI, and sensitivity to traffic exposures. For these tests, age was categorized based on quartiles (≤ 35 , 36–45, 46–58, > 58 years), sensitivity to traffic exposures was split at the median (≤ 15 , > 15), and BMI was categorized into under/normal weight, overweight, and obesity (< 25 , ≥ 25 – 29.99 , $\geq 30\text{ kg/m}^2$). Effect modification was checked in stratified analyses and considered present if the interaction between NDVI_{500-m} and the putative modifier was significant.

In light of available evidence that traffic noise, air pollution, annoyance from traffic-related exposures, mental health problems, and adiposity may mediate the effect of greenspace on health (Markevych et al., 2017), these factors were only used in explorative mediation analyses to minimize the risk of overadjustment (cf. Rothman et al., 2008). Mediation was examined with the help of the PROCESS v 2.16 macro for SPSS (Hayes, 2013). Due to limited statistical power, we only considered the effect of NDVI_{500-m} on continuously-measured blood

pressure. We tested single (mediators one-at-a-time), parallel (mediators together, but working independently), and serial (mediators working together) mediation models. In the serial mediation models, two serial indirect paths were specified: NDVI_{500-m} → L_{dn} → traffic-related annoyance → blood pressure; and NDVI_{500-m} → NO₂ → traffic-related annoyance → blood pressure. 95% confidence intervals for the indirect effects were constructed using bias-corrected bootstrapping (5000 samples).

In a sensitivity analysis, we excluded participants on blood pressure medication and repeated the models for NDVI_{500-m} and systolic/diastolic blood pressure. In another sensitivity analysis, we excluded those with a family history of hypertension.

Results were considered statistically significant at the $p < 0.05$ level (two-tailed). Statistical analyses were conducted with SPSS v. 21 (Armonk, NY: IBM Corp.) and Stata v. 13 (College Station, TX: StataCorp LP.).

3. Results

3.1. Characteristics of the sample and bivariate associations

Characteristics of the 555 participants included are presented in Table 1. Mean age was 46.59 ± 14.83 years and most participants were women. The majority owned their home, had received < 10 years of school education, were non-smokers, did not have a family history of hypertension, were not obese, and had a domestic garden and a balcony. Supplemental Table S1 shows tests of the bivariate associations between participants' characteristics and blood pressure variables. In line with observations in previous literature, residents with hypertension were older, less educated, were more likely to have a family history of hypertension, and to be overweight. In the case of hypotension, it was found more often in women, among those with a family history of hypertension, and with lower weight. Both hyper- and hypotension were inversely related to the level of surrounding greenness. That is, the prevalence of hyper- and hypotension in the lowest quartile of NDVI was 37% and 42%, respectively, and decreased to 14% and 17% in the

Table 1
Descriptive characteristics of the sample ($N = 555$).

Characteristic	Descriptives
Men (n , %)	233 (41.98)
Age (mean years $\pm$ SD)	46.59 $\pm$ 14.83
Home ownership (n , %)	
Owner	417 (75.14)
Renting	94 (16.94)
Co-habitation	44 (7.93)
Education < 10 years (n , %)	354 (63.78)
Smoker (n , %)	153 (27.56)
Hypertension diagnosis (n , %)	81 (14.59)
Hypertension medication (n , %)	95 (17.12)
Hypotension diagnosis (n , %)	82 (14.77)
Hypotension medication (n , %)	57 (10.27)
Systolic blood pressure (mean mm Hg $\pm$ SD)	134.23 $\pm$ 19.40
Diastolic blood pressure (mean mm Hg $\pm$ SD)	85.25 $\pm$ 11.62
Family history of hypertension (n , %)	187 (33.69)
Body mass index (mean kg/m ² $\pm$ SD)	26.13 $\pm$ 4.46
NDVI _{500-m} (median, IQR)	0.67 (0.16)
Domestic garden (n , %)	422 (76.04)
Balcony (n , %)	513 (92.43)
Bluespace _{500-m} (n , %)	426 (76.76)
L _{dn} (mean dB(A) $\pm$ SD)	59.98 $\pm$ 6.83
NO ₂ (mean µg/m ³ $\pm$ SD)	34.31 $\pm$ 3.50
Traffic annoyance (mean $\pm$ SD)	22.06 $\pm$ 13.76
Traffic sensitivity (mean $\pm$ SD)	15.68 $\pm$ 9.36
Mental health problems (GHQ) (mean $\pm$ SD)	21.99 $\pm$ 6.33

Note: GHQ, General Health Questionnaire; IQR, interquartile range; SD, standard deviation; L_{dn}, day-night traffic noise level; NDVI, Normalized Difference Vegetation Index; NO₂, nitrogen dioxide.

highest quartile. As for continuously-measured blood pressure, it was higher in men, less educated and older residents, and those with higher BMI. In addition, diastolic blood pressure was lower in residents who had a domestic garden.

Supplemental Table S2 shows correlations between the main geographic variables. The greenspace metrics were highly inter-correlated (see Supplemental Fig. S1 for distributions of greenspace variables). Notably, due to the specific geographic relationships between traffic sources, the river, and greenspace, distance to bluespace was positively associated with greenspace and inversely with L_{dn} and NO₂, that is, residences farther away from bluespace were exposed to lower levels of L_{dn}, NO₂, and to higher greenspace.

3.2. Multivariate associations between greenspace and blood pressure

Higher NDVI and SAVI were associated with lower odds of hypertension (both doctor-diagnosed and medicated) and doctor-diagnosed hypotension, and lower systolic blood pressure (Table 2). These results were most pronounced for the 300-m and 500-m buffers. For tree cover, a similar pattern was observed for hypotension, but associations were somewhat weaker for hypertension. Additionally, higher tree cover was associated with lower systolic and diastolic blood pressure, but only in the 100-m buffer. Those with a domestic garden had lower diastolic blood pressure. No associations were observed for the other greenspace metrics.

3.3. Effect modification, mediation, and sensitivity analyses

Table 3 shows results of the tests of potential modifiers. Higher NDVI_{500-m} was stronger associated with lower systolic blood pressure in those having a domestic garden, while the effect on diastolic blood pressure was stronger in overweight/obese participants.

Tests of the mediation models indicated that the effect of NDVI_{500-m} on continuously-measured blood pressure was independent of L_{dn}, NO₂, traffic-related annoyance, mental health problems, and BMI (Supplemental Table S3).

In the sensitivity analysis, NDVI_{500-m} was still associated with lower systolic blood pressure ($\beta = -3.36$; 95% CI: $-6.24, -0.48$) in the subgroup who were not taking any blood pressure medication. In the case of diastolic blood pressure, the effect estimate increased, but remained non-significant ($\beta = -1.17$; 95% CI: $-3.10, 0.75$). In the subgroup without a family history of hypertension, we found no effect on systolic ($\beta = -1.81$; 95% CI: $-4.98, 1.36$) and diastolic blood pressure ($\beta = -1.19$; 95% CI: $-2.78, 0.40$).

4. Discussion

4.1. Major findings

This is one of the few studies evaluating the relationship between residential greenspace and blood pressure. Higher overall greenness, as measured by NDVI and SAVI, was associated with lower odds of hyper/hypotension and lower levels of systolic blood pressure. Similar pattern was revealed for tree cover, however, associations with hypertension were less consistent across buffers, and systolic/diastolic blood pressure were lower only in association with greenness in the 100-m buffer. Having a domestic garden was associated with lower diastolic blood pressure readings. Residing near to forests, agricultural land, or urban green spaces was not related to blood pressure. We found no evidence that mediation was responsible for the observed effects.

These findings concur with some earlier studies. For example, Jia et al. (2018) evidenced 55–85% reduced odds of hypertension in people exposed to high NDVI compared with their counterparts, and Brown et al. (2016) found 13% lower odds per one standard deviation increase in NDVI. Jendrossek et al. (2017), however, did not observe an effect on maternal hypertension, where other circumstances/factors may be of

Table 2
Associations between different residential greenspace and blood pressure metrics (N = 555).

Greenspace metric	Hypertension (OR; 95% CI)		Hypotension (OR; 95% CI)		Blood pressure (β ; 95% CI)	
	Diagnosis	Medication	Diagnosis	Medication	Systolic	Diastolic
NDVI						
100-m	0.74 (0.59, 0.93)*	0.79 (0.59, 1.06)	0.90 (0.68, 1.18)	1.02 (0.67, 1.55)	−1.57 (−3.41, 0.28)	−0.96 (−2.11, 0.19)
300-m	0.66 (0.57, 0.76)*	0.63 (0.52, 0.76)*	0.63 (0.45, 0.88)*	0.80 (0.52, 1.22)	−3.02 (−5.07, −0.98)*	−0.70 (−2.23, 0.83)
500-m	0.64 (0.52, 0.78)*	0.58 (0.47, 0.72)*	0.60 (0.44, 0.82)*	0.78 (0.49, 1.24)	−2.84 (−5.06, −0.62)*	−0.92 (−2.33, 0.50)
1000-m	0.59 (0.42, 0.81)*	0.59 (0.42, 0.83)*	0.58 (0.41, 0.83)*	0.65 (0.41, 1.04)	−2.94 (−5.20, −0.68)*	−1.36 (−3.03, 0.32)
SAVI						
100-m	0.77 (0.56, 1.04)	0.75 (0.51, 1.11)	0.90 (0.64, 1.25)	1.02 (0.65, 1.62)	−1.49 (−3.18, 0.20)	−0.86 (−2.26, 0.55)
300-m	0.66 (0.57, 0.76)*	0.63 (0.52, 0.76)*	0.63 (0.45, 0.88)*	0.80 (0.52, 1.22)	−3.02 (−5.07, −0.98)*	−0.70 (−2.23, 0.83)
500-m	0.71 (0.51, 0.99)*	0.61 (0.45, 0.83)*	0.72 (0.49, 1.04)	0.80 (0.56, 1.15)	−2.47 (−4.12, −0.82)*	−0.77 (−2.38, 0.84)
1000-m	0.80 (0.52, 1.22)	0.74 (0.47, 1.16)	0.76 (0.48, 1.21)	0.77 (0.52, 1.14)	−2.45 (−3.92, −0.99)*	−1.01 (−2.76, 0.75)
Tree cover density (%)						
100-m	0.87 (0.73, 1.04)	0.91 (0.79, 1.06)	1.16 (0.99, 1.35)	0.92 (0.72, 1.18)	−1.38 (−2.55, −0.22)*	−0.67 (−1.23, −0.11)*
300-m	0.81 (0.68, 0.95)*	0.89 (0.70, 1.13)	0.73 (0.61, 0.87)*	1.00 (0.69, 1.43)	−0.84 (−2.65, 0.97)	−0.10 (−0.69, 0.50)
500-m	0.78 (0.58, 1.03)	0.82 (0.62, 1.09)	0.71 (0.50, 0.99)*	1.02 (0.59, 1.75)	−1.11 (−2.30, 1.09)	−0.23 (−1.004, 0.55)
1000-m	0.69 (0.55, 0.87)*	0.70 (0.54, 0.92)*	0.75 (0.62, 0.90)*	0.88 (0.53, 1.48)	−0.77 (−2.49, 0.95)	−0.32 (−1.16, 0.51)
Forest area present						
> 300-m	1.00	1.00	1.00	1.00	0.00	0.00
101–300-m	0.69 (0.41, 1.15)	0.76 (0.47, 1.24)	0.89 (0.60, 1.31)	0.99 (0.44, 2.24)	−1.02 (−3.33, 1.29)	−0.02 (−2.60, 2.56)
≤ 100-m	0.85 (0.44, 1.64)	1.21 (0.65, 2.24)	0.63 (0.27, 1.49)	0.63 (0.35, 1.14)	−1.57 (−7.56, 4.42)	1.28 (−0.94, 3.50)
Agricultural land present						
> 300-m	1.00	1.00	1.00	1.00	0.00	0.00
101–300-m	0.69 (0.29, 1.68)	0.74 (0.28, 1.93)	1.14 (0.68, 1.90)	0.59 (0.24, 1.47)	0.35 (−3.77, 4.47)	−0.65 (−4.12, 2.83)
≤ 100-m	0.64 (0.30, 1.36)	0.61 (0.27, 1.41)	1.01 (0.46, 2.22)	0.92 (0.29, 2.87)	−0.44 (−5.17, 4.29)	−1.21 (−3.96, 1.53)
Urban green space present						
> 500-m	1.00	1.00	1.00	1.00	0.00	0.00
301–500-m	1.06 (0.53, 2.11)	1.45 (0.80, 2.64)	1.50 (0.96, 2.37)	1.73 (0.89, 3.37)	1.60 (−3.07, 6.28)	0.67 (−1.82, 3.16)
≤ 300-m	1.22 (0.64, 2.32)	1.32 (0.65, 2.71)	1.51 (0.97, 2.37)	1.20 (0.57, 2.51)	2.17 (−0.45, 4.80)	0.21 (−1.34, 1.76)
Having a domestic garden	0.75 (0.32, 1.80)	0.81 (0.42, 1.58)	0.90 (0.66, 1.23)	1.25 (0.64, 2.45)	−3.58 (−8.49, 1.33)	−3.02 (−4.54, −1.49)*
Having a balcony	1.25 (0.74, 2.12)	0.56 (0.21, 1.50)	1.07 (0.59, 1.94)	0.49 (0.09, 2.58)	−3.47 (−8.72, 1.78)	0.33 (−3.43, 4.09)

Note: NDVI, Normalized Difference Vegetation Index; SAVI, Soil Adjusted Vegetation Index.

Models are adjusted for age, sex, education, home ownership, person/rooms, smoking, family history of hypertension, and presence of bluespace in the respective buffer (distance to bluespace in the models for Forest area presence, Agricultural land presence, and Urban green space presence; the models for garden and balcony were not adjusted for bluespace).

Coefficients are odds ratios (OR) or unstandardized linear regression coefficients (β) with their 95% confidence intervals.

Effect estimates of NDVI, SAVI, and tree cover are reported per interquartile range increase.

* Coefficient is statistically significant at $p < 0.05$.

higher importance. In another study, hypertension was not related to land use-defined greenspace, similarly to our findings (Picavet et al., 2016). Unlike Picavet et al. (2016), we found no differential effect on continuously-measured blood pressure across different land use types of greenspace. Lane et al. (2017) indicated a 4.3 mm Hg increase in systolic blood pressure per IQR decrease in NDVI. Another study (Bijnens et al., 2017) showed that early-life exposure to higher greenness was associated with a 3.59 mm Hg lower night-time systolic blood pressure in adulthood. Such a clinically small change in blood pressure may have a huge public health importance. A population-wide reduction of 2 mm Hg systolic blood pressure, which was observed here, could decrease adverse cardiovascular events by some 10–20% (Hardy et al., 2015). Our findings appear also relevant to medical practice when we consider that the associations were linear and held for diagnosed hyper/hypotension. In light of increasing prevalence of hypertension in Austria over the past decades (Großschädl et al., 2015), our findings encourage the consideration of residential greenspace as a protective factor that may support normal levels of blood pressure.

As far as we are aware, no earlier study has investigated effects on hypotension. We proposed that, since greenspace can mitigate traffic noise (Dzhambov et al., 2018b), noise reduction may stand on the way from greenspace to lower blood pressure. We base this on previous findings of an association between hypotension and traffic noise; this effect was explained by increased parasympathetic activity and vegetative lability to environmental changes (weather sensitivity) – mainly in younger women, – which in turn compromised regulation of the

autonomous nervous system (Lercher and Widmann, 2013; Lercher et al., 2014). A recent animal experiment highlighted how changes in DNA methylation of brain-derived neurotrophic factor and catechol-O-methyltransferase genes may ensue from noise exposure, and thereby decrease blood pressure and body weight (Guo et al., 2017). In addition, greenspace may protect against mental ill-health (Gascon et al., 2018; Dzhambov et al., 2018a), and anxiety and depression have been associated with low blood pressure, controlling for cardiovascular disease status, smoking, and adiposity (Hildrum et al., 2007). However, currently, no clear mechanistic hypothesis exists to explain our findings. Given that the effect on hypotension was the most consistent in our study, it deserves future consideration.

The large effect sizes for the NDVI associations and their robustness to relevant adjustments may be due to the relatively higher greenness level in our study area compared with previous studies (Markevych et al., 2014; Yitshak-Sade et al., 2017; Brown et al., 2016; Jia et al., 2018). Interestingly, we found no indication for an indirect effect on blood pressure. Similarly to our findings, Vienneau et al. (2017) observed a protective effect of greenspace on hypertension-related mortality that was largely independent of transportation noise and air pollution, which mediated < 10% of the effect. However, the amount of greenness cannot explain why other authors noted no materially important confounding by noise and air pollution even in less green areas (Markevych et al., 2014; Bijnens et al., 2017; Yitshak-Sade et al., 2017). These null findings suggest that there could be more influential modifiers/mediators underlying the effect of greenspace on blood pressure.

Table 3Effect modification of the association between residential greenness (Normalized Difference Vegetation Index_{500-m}) and continuously-measured blood pressure.

Effect modifier	N	Systolic blood pressure		Diastolic blood pressure	
		β (95% CI)	p-Value interaction	β (95% CI)	p-Value interaction
Sex			0.185		0.158
Male	233	−3.41 (−8.12, 1.30)		−1.85 (−4.59, 0.89)	
Female	322	−2.11 (−3.90, −0.33)*		−0.40 (−2.28, 1.49)	
Age			0.891		0.484
≤35 years	157	−2.86 (−6.59, 0.87)		1.13 (−1.69, 3.96)	
36–45 years	134	−3.98 (−9.49, 1.53)		−2.84 (−6.96, 1.27)	
46–58 years	133	−4.17 (−9.57, 1.24)		−2.98 (−5.33, −0.63)*	
58–81 years	131	−0.57 (−5.43, 4.29)		0.03 (−1.68, 1.74)	
Education			0.791		0.205
<10 years	354	−2.31 (−4.20, −0.41)*		−0.96 (−2.94, 1.01)	
≥10 years	201	−3.25 (−6.99, 0.50)		−0.62 (−1.92, 0.69)	
Domestic garden			0.015		0.158
No	133	3.37 (−3.32, 10.05)		0.70 (−3.57, 4.97)	
Yes	422	−4.04 (−6.37, −1.70)*		−0.73 (−1.90, 0.44)	
Balcony			0.278		0.723
No	42	9.48 (−7.95, 26.91)		4.05 (−9.29, 17.39)	
Yes	513	−2.98 (−5.42, −0.53)*		−0.96 (−2.14, 0.21)	
Body mass index			0.771		0.002
16.36–25 kg/m ²	238	−1.37 (−4.18, 1.44)		2.33 (0.18, 4.48)*	
25–29.99 kg/m ²	230	−4.10 (−9.40, 1.19)		−1.63 (−4.20, 0.94)	
30–50.78 kg/m ²	87	−1.87 (−5.01, 1.28)		−3.60 (−6.43, −0.77)*	
Traffic sensitivity			0.540		0.185
Low	282	−3.45 (−4.81, −2.09)*		−1.47 (−3.19, 0.25)	
High	273	−2.25 (−7.24, 2.74)		−0.15 (−2.42, 2.11)	

Note: Models are adjusted for age, sex, education, home ownership, person/rooms, smoking, family history of hypertension, and presence of bluespace in the 500-m buffer (unless stratified by the respective factor).

Coefficients are unstandardized linear regression coefficients (β) with their 95% confidence intervals.

Effect estimates are reported per interquartile range increase of Normalized Difference Vegetation Index.

* Coefficient is statistically significant at $p < 0.05$.

For instance, higher greenness and better access to green spaces are associated with higher restorative quality in the neighborhood, and thus, can encourage recreational physical activity and social interactions (cf. Markevych et al., 2017). In turn, higher levels of physical activity (Huai et al., 2013) and neighborhood social cohesion (Lagisetty et al., 2016) may be protective against hypertension. This is illustrated in the study of Jia et al. (2018), in which around 50% of the association between NDVI and hypertension was accounted for by physical exercise. However, the picture is not clear – according to Markevych et al. (2014), the effect on children's blood pressure was independent of physical activity. Although we did not collect data on physical activity and gardening, we observed a positive association with lower systolic blood pressure only in residents having a domestic garden. One could assume that this finding is due to the fact that gardens encourage horticulture which typically involves moderately intensive physical activity, as well as close contact with nature (Park et al., 2008; van den Berg et al., 2010; Park et al., 2014). Therefore, other authors may wish to consider a more holistic model, in which restorative/stress buffering effects, physical activity, and social cohesion mediate the observed associations of greenspace on blood pressure.

Among the effect modifiers tested, we found a stronger association between NDVI_{500-m} and systolic blood pressure in residents having a domestic garden. In addition, having a garden was itself associated with lower diastolic blood pressure, possibly because environmental experiences in gardens support restoration (Dahlkvist et al., 2016). A meta-analysis indicated that gardens not only encourage physical activity (gardening), but also reduce anxiety/depression and enhance sense of community (Soga et al., 2017). In addition, simply viewing nature constitutes a micro-restorative episode and buffers stress (Ulrich, 1984; Lee et al., 2015), which may also explain why NDVI was associated with lower systolic blood pressure only in those who had a balcony, although the interaction was non-significant. Mitchell and Popham (2007) speculated that residential greenspace was associated with better health only in low-income areas because in more affluent

neighborhoods domestic gardens were more important than municipal greenspace. However, although in our sample < 40% of participants had a higher education, over 70% owned their home and had a domestic garden. We found no effect modification by education, a proxy for socioeconomic status in our study, while Vienneau et al. (2017) found a stronger effect among residents with higher socio-economic position, and Brown et al. (2016) reported stronger health-supportive relationships only in low- and medium-income neighborhoods. Such contrasting findings could be explained by the lower urbanization in our study area – Ruijsbroek et al. (2017), for example, hypothesized that green spaces may be more important for the health of low-educated residents mostly in highly urbanized areas. Another more unexpected finding of the present analyses was that among overweight/obese residents NDVI had a stronger effect on diastolic blood pressure. However, for this interaction no ready explanation is available in the literature and warrants further investigation and replication.

4.2. Strengths and limitations

The present study contributes to the thin body of evidence on greenspace and cardiovascular disease. In their recent systematic review, Twohig-Bennett and Jones (2018) identified 13 studies on greenspace and systolic/diastolic blood pressure, and only four that considered hypertension. In addition to paucity of research, those authors found high between-study heterogeneity.

Our study makes some new contributions to the field. Unique features are the location of the study area, where high levels of traffic pollution and natural beauty of an Alpine valley collide, and the consideration of hypotension as a potential outcome of greenspace. We also employed a range of greenspace metrics, which has only been done in studies on mental health (Dzhambov et al., 2018a). Furthermore, we included the presence of a domestic garden and balcony, two potential resources for close interaction with nature while at home. We collected data on multiple confounding and modifying factors, which no previous

study has examined as a set. Precise and repetitive measurements of blood pressure and application of several definitions of high and low blood pressure are also clear strengths. Owing to the random sampling and sufficient representativeness of participants' characteristics, our findings can be generalized to the population of the Lower Inn Valley.

Several limitations deserve consideration. The cross-sectional design is an obvious draw-back because we cannot make formal claims of causation. However, there is ground for the assumption that the observed associations may not be spurious. We only considered hyper/hypotension reported during the last 12 months, and most participants were long-term residents (> 20 years), meaning that they had been exposed to the same amount of greenspace for many years before they were diagnosed. Moreover, reversed causality between objective greenspace and health cannot be expected, unless healthier people had moved to greener neighborhoods, which was unlikely owing to economic constraints. However, we acknowledge that results of our preliminary mediation analysis do not rule out the presence of indirect paths, which could be revealed in future longitudinal studies (cf. Maxwell et al., 2011; Dormann and Griffin, 2015).

Critics may challenge the validity of self-reported diagnosis and medication use as indicators for disease status. Although objectively-assessed hypertension based on medical records or blood pressure readings seems attractive, it has been scrutinized as one possible reason for null results in epidemiological studies on traffic noise and hypertension (Dzhambov and Dimitrova, 2018). Self-reports inform about a sustained high blood pressure, while single measurements may yield more false positive cases (Fuks et al., 2017; Dzhambov and Dimitrova, 2018). In fact, self-reported hypertension and antihypertensive medication have good sensitivity and specificity (77.1% and 93.4% for hypertension and 92.4% and 86.4% for antihypertensive medication, respectively) compared with clinical diagnoses and pharmacy insurance claims (de Menezes et al., 2014; Fujita et al., 2015).

We did not have data on some potentially important factors, such as physical activity and social cohesion. We also found no protective effect of bluespace, possibly because the major transportation lines in the valley follow the course of the river Inn.

We used education as a dichotomized indicator for individual-level socioeconomic status. However, direct comparison with previous studies is hindered by the fact that the difference in socioeconomic inequality in our sample may not be as pronounced as in a typical city population. In addition, we lacked data on area-level socioeconomic status. Both of these are considered important cofounders (Markevych et al., 2017), but it is unknown whether this holds in peri-urban settlements in an Alpine valley.

We used NO₂ as a proxy for traffic-related air pollution because of its spatial correlations with other components of air pollution (Levy et al., 2014), because it is the most commonly reported indicator in the literature (Khan et al., 2018), and because in the study area NO₂ has the highest correlation with traffic (between 70% and 80%, depending on season). Nevertheless, other contaminants, such as fine particles, are also associated with hypertension and should be explored further (Yang et al., 2018).

We could not assess what activities participants performed in green spaces or the quality and real accessibility of those green spaces, which are important aspects that deserve consideration (Shanahan et al., 2016; Markevych et al., 2017). In addition, NDVI was calculated from a single satellite image, however, NDVI spatial contrast over seasons and years can generally be considered relatively stable (cf. Dadvand et al., 2012; Gascon et al., 2016). Finally, the objective greenspace metrics considered here were remotely-sensed. Recently, commercially available engines like Google Street View have allowed assessment of greenspace visible from the eye-level (Lu, 2018), but no suitable images were available from the sampling period. Nowadays, GPS tracking enables researchers to assess greenspace along people's daily activity places and their mobility path (Helbich, 2018); however, we relied on a static exposure assessment approach because such technology was not

available at the time of the survey. Although future research should address all these limitations common in many greenspace studies (cf. Markevych et al., 2017; Nieuwenhuijsen et al., 2017), we reckon that they do not fully offset the strengths of our study.

5. Conclusions

Higher residential greenness was linearly associated with lower prevalence of hyper- and hypotension and lower systolic blood pressure across different buffer sizes. Similar pattern was revealed for tree cover, however, associations with hypertension were less consistent across buffers, and systolic and diastolic blood pressure were lower only in association with greenness in the 100-m buffer. Having a domestic garden also seemed protective of high diastolic blood pressure. Residing near to forests, agricultural land, or urban green spaces was not related to blood pressure. Higher greenness was stronger associated with lower systolic blood pressure in those having a domestic garden, while the effect on diastolic blood pressure was stronger in overweight/obese participants. These findings support the idea that greenspace should be considered as protective of both high and low blood pressure, however, underlying mechanisms remain insufficiently understood.

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Competing financial interests

The authors declare they have no actual or potential competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2018.09.044>.

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