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Satellite-derived data on greenness and access to green spaces are related to children's health indicators

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Summary

There is increasing epidemiologic evidence on beneficial effects of green environments on survival, perceived health and quality of life, mental health, obesity and physical activity. However, most studies have been conducted in adults. Further research to assess the impacts of green environments on children's health is warranted. Moreover, an investigation of potential mechanisms underlying the associations is required.

This thesis comprises three publications, which are based on data from the German birth cohorts GINIplus and LISAplus.

The first publication assessed the effects of residential greenness at the mother's residential address as well as access to green spaces assessed by satellite-derived data on birth weight of newborns. Greenness in a 500-m buffer around the mother's residential address at delivery was positively associated with the birth weight of neonates. Air pollution, noise, population density and maternal stress during pregnancy did not mediate the discovered association. In the stratified analyses, the association between greenness and birth weight was more pronounced in mothers with low socioeconomic status. Access to green spaces and birth weight were not associated. Thus, increased accessibility to green spaces also does not explain the observed association with greenness.

The second publication investigated whether access to green spaces as well as residential greenness are associated with behavioural problems in 10-year-old children. Hyperactivity/inattention and peer relationship problems were positively associated with increasing distances to urban green spaces. The observed association with hyperactivity/inattention was only statistically significant among males. Children living further than 500 m away from any urban green space had more overall behavioural problems than those living within 500 m of an urban green space. Behavioural problems were not associated with the distance to a forest or with residential surrounding greenness. Thus, our findings suggest beneficial effects of living in close proximity to well-maintained green spaces on children's mental health.

The third publication explored for the first time an association between residential greenness and blood pressure in 10-year-old children. The found association was not influenced by environmental stressors (ambient temperature and air pollution, noise annoyance, altitude and level of urbanisation). The discovered link is in line with the existing evidence from experimental studies and thus, with the psychoevolutionary theory of Ulrich; the latter argues that green environments mitigate stress by activating the parasympathetic system. The associations were only significant in the urban Munich study area but null in the rural Wesel area. This result might indicate that children living in urbanised regions, which generally lack vegetation, might benefit more from high residential greenness than those from the rural areas.

In summary, these results support the hypothesis that better access to green spaces as well as higher residential surrounding greenness benefit children health. The results of my thesis suggest that greenness might improve health through the mech-

anism of physiological stress alleviation. But, contrary to my expectations, the observed effects of greenness and green spaces could not be additionally explained by mediation via physical activity, air pollution, noise, or urbanisation, possibly, because of insufficient data. Thus, future research should test more specifically what stands behind the discovered associations. Finally, health impacts of green environments on children's health should be further investigated in different geographic areas with incorporation of data on time spent in the neighbourhood and the activities conducted as well as area-level socioeconomic status.

Zusammenfassung

Wohnen in einer grünen Umgebung hat möglicherweise positive Auswirkungen auf Mortalität, subjektive Gesundheit, die Lebensqualität und psychische Gesundheit, Adipositas und körperliche Aktivität. Allerdings wurden die meisten epidemiologischen Studien bei Erwachsenen durchgeführt. Weitere Forschung zur Untersuchung des Einflusses von grünen Umgebungen auf die Gesundheit von Kindern ist erforderlich. Darüber hinaus besteht Bedarf an der Klärung der möglichen, zugrunde liegenden Mechanismen.

Diese Dissertation umfasst drei Publikationen, welche auf Daten der deutschen Geburtskohortenstudien GINIplus und LISAplus basieren.

Die erste Publikation befasst sich mit dem Zusammenhang zwischen der Vegetationsintensität in der Wohnumgebung der Mutter (basierend auf Satellitenbildern) und dem Geburtsgewicht von Neugeborenen. Eine höhere Vegetationsintensität in einem Radius von 500 m um die Wohnadresse der Mutter war mit einem höheren Geburtsgewicht der Neugeborenen assoziiert. Der beobachtete Effekt wurde nicht durch solche Faktoren wie Luftverschmutzung, Lärm, Bevölkerungsdichte und mütterlichen Stress während der Schwangerschaft beeinflusst. Der stärkste Zusammenhang zwischen der Vegetationsintensität und dem Geburtsgewicht wurde für Mütter mit einem niedrigen sozioökonomischen Status beobachtet. Der Zugang der Mütter zu Grünflächen und das Geburtsgewicht der Kinder waren nicht assoziiert. Ein besserer Zugang zu Grünflächen erklärt daher nicht den beobachteten Effekt für die Vegetationsintensität.

In der zweiten Publikation wurde untersucht, ob ein besserer Zugang zu Grünflächen mit Verhaltensauffälligkeiten bei 10-jährigen Kindern assoziiert ist. Es wurde ein Zusammenhang zwischen einer größeren Distanz zu städtischen Grünflächen und mehr Hyperaktivität/Unaufmerksamkeit sowie Problemen im Umgang mit Gleichaltrigen beobachtet. Der beobachtete Zusammenhang mit Hyperaktivität/Unaufmerksamkeit war nur bei Jungen statistisch signifikant. Kinder, die weiter als 500 m von einer städtischen Grünfläche entfernt lebten, hatten insgesamt mehr Verhaltensauffälligkeiten als diejenigen, die weniger als 500 m entfernt von einer städtischen Grünfläche wohnen. Die Entfernung zu einem Wald oder die Vegetationsintensität in der Wohnumgebung waren nicht mit Verhaltensauffälligkeiten assoziiert. Unsere Ergebnisse sprechen für eine positive Auswirkung von städtischen Grünflächen in der Wohnumgebung auf die psychische Gesundheit von Kindern.

In der dritten Publikation wurde ein Zusammenhang zwischen einer höheren Vegetationsintensität in der Wohnumgebung und einem niedrigeren Blutdruck bei 10-jährigen Kindern gefunden. Der beobachtete Effekt wurde nicht durch Umweltfaktoren wie Umgebungstemperatur, Luftverschmutzung, Lärmbelästigung, Höhenlage und Grad der Urbanisierung beeinflusst. Diese Ergebnisse stützen bisherige Erkenntnisse aus experimentellen Untersuchungen und damit auch die psychoevolutionäre Theorie von Ulrich. Diese Theorie besagt, dass grüne Umgebungen Stress durch die Aktivierung des Parasympathikus abbauen. Ein signifikanter Zusammenhang

zwischen Vegetationsintensität und Blutdruck wurde nur bei Kindern beobachtet, welche in der städtischen Münchner Region wohnten. Für Kinder in der ländlichen Region Wesel gab es einen solchen Zusammenhang nicht. Dieses Ergebnis könnte darauf hindeuten, dass Kinder, die in urbanen Regionen, in denen es tendenziell eher an Vegetation mangelt, wohnen, mehr von einer höheren Vegetationsintensität profitieren könnten, als diejenigen aus ländlichen, eher grünen Gebieten.

Die Ergebnisse dieser drei Publikationen stützen die Hypothese, dass ein besserer Zugang zu Grünflächen sowie eine höhere Vegetationsintensität in der Wohnumgebung positive Auswirkungen auf die Gesundheit von Kindern haben. Basierend auf diesen Ergebnissen könnte physiologischer Stressabbau den positiven Einfluss von Vegetation teilweise erklären. Wider Erwarten konnten Faktoren wie körperliche Aktivität, Luftverschmutzung, Lärm oder Urbanisierung die beobachteten Effekte von Vegetationsintensität und Zugang zu Grünflächen nicht zusätzlich erklären, möglicherweise wegen unzureichender Daten. So sollten zukünftige Studien weiter untersuchen, was hinter den beobachteten Assoziationen stehen könnte. Zusätzlich sollte der Einfluss von grünen Umgebungen in verschiedenen geografischen Regionen untersucht werden, möglichst unter Berücksichtigung von Daten zur durchschnittlichen Zeit, welche die Teilnehmer im Freien verbringen, zur Art der Aktivitäten im Freien und zu sozioökonomischen Faktoren.

1 Introduction

1.1 Nature and health

For centuries, contact with nature has been believed to benefit both mental and physical health. Recently, investigating the health effects of nature attracts a lot of attention by leading researchers in the world. There is increasing epidemiologic evidence on beneficial effects of green environments. In particular, exposure to nature improves survival (1–3), perceived health and quality of life (4,5), and mental health (6–11) prevents obesity (10,12–14) and promotes physical activity (10,15,16). However, most studies have been conducted in adults, and, to date, the impacts of green environments on children's health have not sufficiently been investigated.

Several plausible biological mechanisms have been suggested to explain positive effects of green environments on health. First of all, city plants have been shown to improve air quality through decreasing levels of air pollutants (17–19) and to moderate ambient temperature (20), which both have been demonstrated to affect numerous health outcomes. Furthermore, higher exposure to green environments enhances the level and frequency of physical activity (10, 21), and promotes social contacts which also leads to improved health through the encouraging of spending time outdoors (9, 22, 23). Finally, any green environments-related benefits may be explained by mitigating physiological stress (24, 25) as well as by inducing recovery from mental fatigue (26).

Further insight into the effects of green environments on health, especially, of children, as well as better understanding the pathways through which these effects occur is needed to derive an objective data basis for efficient city planning and the development of effective health policies.

1.2 Measuring of exposure to green environments

For decades, despite of the big interest in potential health impacts of green environments, lack of methods to estimate exposure to them objectively made such epidemiological research challenging. Instead, subjective measures to assess green environments' exposure were widely used. Subjective (or perceived) measures of green environments' exposure are typically questionnaire-based, asking the respondents about how far from green spaces they live, how safe and well-maintained these green spaces are, how often and in which way the respondents use them, and how green and esthetically pleasant their neighbourhoods are (27–29).

Recently, objective measures of green environments are becoming more common. The reasons for that are wide spread of Geographic Information System (GIS) technologies as well as availability (often, for free) of processed and raw satellite images covering the entire surface of the planet. Typically, objective measures characterise general level of vegetation at the place of the residence, the proximity of structured green spaces to the residential address, and the amount (in square metres/ kilometres or percent) of structured green spaces in the neighbourhood defined in different ways (27–29). Brand new development of objective methods is an employment of the global positioning systems (GPS) to assess green environments use in addition to their accessibility (15).

In this thesis, I focused on objective measures of exposure to green environments—access to green spaces and residential greenness. Objective (GPS-derived) or subjective (questionnaire-derived) measures of green spaces' use were not available.

2 Specific aims and results

2.1 Specific aims

The thesis is based on the hypothesis that children benefit from better access to green spaces as well as higher residential surrounding greenness, and aims to investigate some of these beneficial effects as well as potential mechanisms underlying them. The objectives were:

- To assess the association between surrounding greenness at mother's residence and the birth weight of newborns.
- To investigate the effects of urban green spaces on behavioural problems.
- To explore whether residential surrounding greenness is associated with blood pressure (BP).

The thesis comprises three manuscripts that have been published in Health & Place, Environment International and BMC Public Health. For all three publications, I developed the research question, study design, performed the statistical analyses and interpreted the results. The comments and suggestions from my supervisors and co-authors as well as from the reviewers were incorporated in the final versions.

2.2 Study population and methods

2.2.1 Study population

All three manuscripts are based on data from two ongoing German birth cohorts: the "German Infant Study on the Influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development" (GINIplus) and the "Influence of Life-Style Factors on the Development of the Immune System and Allergies in East and West Germany plus the Influence of Traffic Emissions and Genetics" (LISAplus). Both cohorts have similar study designs and recruited only healthy full-term neonates with a normal birth weight. Briefly, GINIplus participants were recruited in the cities of Munich (n = 2,949) and Wesel (n = 3,042) between 1995 and 1998. This cohort consists of two study groups: an observational study group and a study group that participated in an intervention trial with hypoallergenic formulae (30, 31). LISAplus participants were recruited in the cities of Munich (n = 1,465), Leipzig (n = 976), Wesel (n = 348) and Bad Honnef (n = 306) between 1997 and 1999 (32, 33). Due to availability of address and geographic information, the first and second manuscripts are based on the Munich subsample of the GINIplus and LISAplus cohorts, while the third manuscript also incorporated data from the participants recruited in the Wesel study centre.

2.2.2 Residential greenness and access to green spaces

Greenness was assessed using the Normalized Difference Vegetation Index (NDVI) which was derived from Landsat 5 Thematic Mapper (TM) satellite images (freely available at `http://earthexplorer.usgs.gov/`). NDVI is a common indicator of green vegetation which was developed to analyse surface reflectance measurements. NDVI is based on two vegetation-informative bands—near-infrared (NIR) and visible red (RED)—and is calculated using the formula

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}.$$

NDVI values range from -1 to $+1$, where $+1$ indicates a high density of green biomass, -1 represents water features and values close to zero refer to barren areas of rock, sand or snow (34). For both Munich and Wesel study areas, we downloaded cloud-free images taken during summer months. Based on these images, NDVI values were calculated at a resolution of 30 m by 30 m (Figure 1); negative values were excluded before further calculation. Residential surrounding greenness was defined as the mean of NDVI values in circular 100-m to 800-m buffers around each participant's home address (Figure 2). These exposure variables were used in all three publications.

Data to calculate access to green spaces were obtained from the local Bavarian land use dataset from the Bavarian Survey Office, and were available only for the

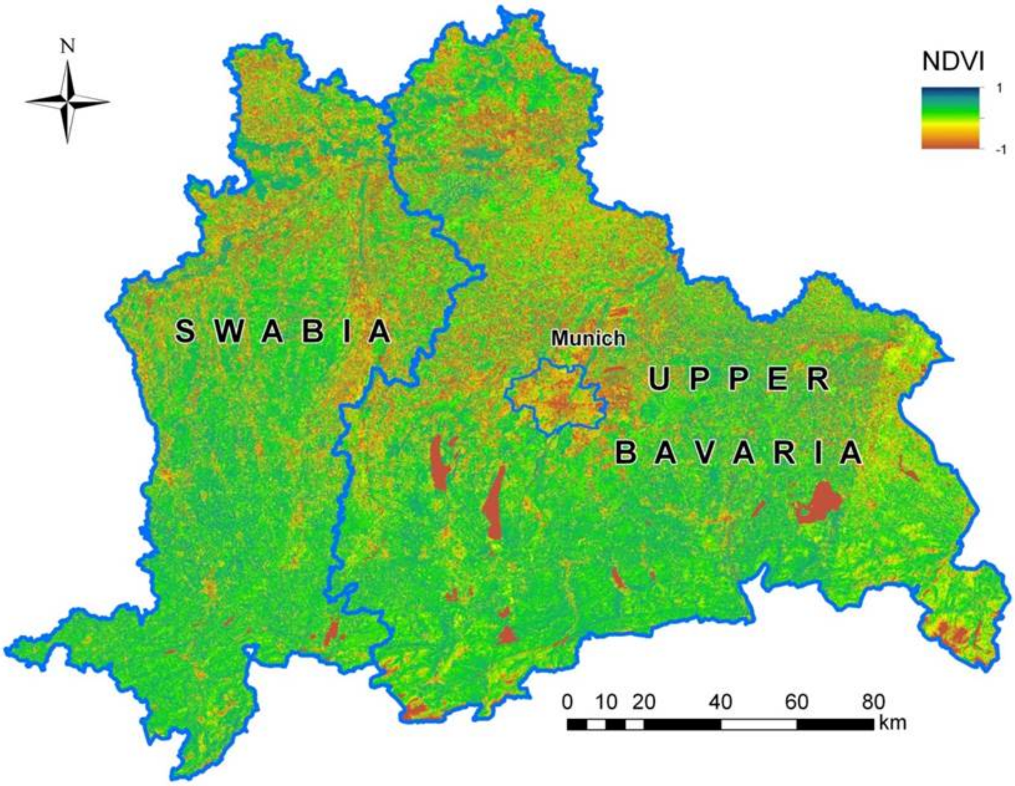

Figure 1: NDVI map of the Munich study area.

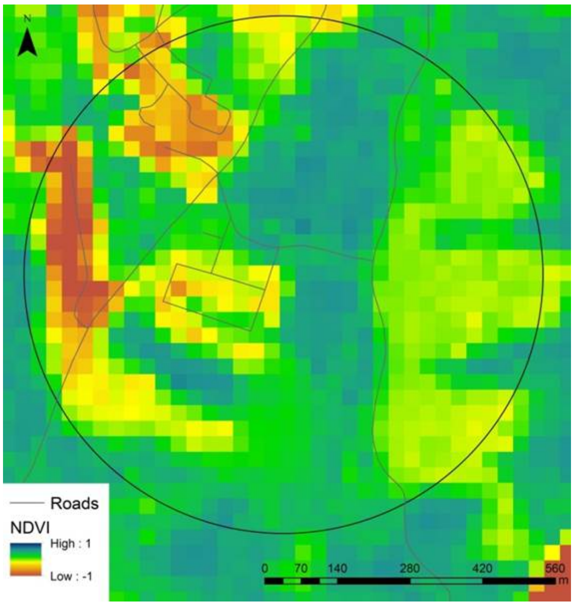

Figure 2: Greenness in a 500-m buffer around participant's home.

Munich study area. Access to urban and natural green spaces was defined as: (i) the Euclidean distance between each child's place of residence and the nearest urban green space (in metres; second publication, Figure 3); (ii) presence of green spaces in a circular 500-m buffer around participant's home (second publication); (iii) area of green spaces in a 500-m buffer around participant's home (first publication).

Figure 3: Access to green spaces.

2.2.3 Analyses

The first publication (chapter 5) assessed the effects of residential greenness at the mother's residential address as well as access to green spaces on birth weight of newborns. Additionally, the potential mechanisms (air pollution decrease, noise reduction, lower urbanisation level and alleviation of maternal stress during pregnancy) underlying the association were explored. The weight of the neonates at birth was measured by physicians during a clinical examination while information on the home address, socioeconomic characteristics of parents, and lifestyle factors was derived from parent-completed questionnaires. Associations were assessed using multivariable linear regressions among 3,203 singleton births, recruited in the city of Munich.

The second publication (chapter 6) investigated whether access to green spaces as well as residential greenness are associated with behavioural problems in 10-year-old children. Behavioural problems (overall mental health, emotional symptoms, conduct problems, hyperactivity/inattention, and peer relationship problems) were assessed by using the Strengths and Difficulties Questionnaire (SDQ; freely available at `http://www.sdqinfo.com/`) and grouped into normal, borderline and abnormal categories (35, 36). Associations between access to urban green spaces and behavioural problems were assessed using proportional odds and logistic regression models in 1,932 children living in the city of Munich and its surrounding areas.

The third publication (chapter 7) explored whether residential greenness is associated with BP in 10-year-old children. Systolic and diastolic arterial BPs were measured twice during a physical examination, and then the average of two measurements was calculated. Generalized additive models (GAMs) assessed associations between BP and residential greenness categorized into tertiles in 2,078 children residing in the Munich and Wesel study areas.

2.3 Results

In the first publication, greenness in a 500-m buffer around the mother's residential address at birth was positively associated with the birth weight of newborns in the city of Munich and its surrounding areas. This finding is in line with the results of few previous studies on greenness and birth weight. Also, similarly to other studies which have investigated the effects of green spaces and greenness, in the stratified analyses, the association between greenness and birth weight was only significant for mothers who attended school for less than 10 years. Surprisingly, air pollution, noise, population density and maternal stress during pregnancy do not appear to be influential factors for this association. Thus, the mechanisms underlying the discovered association remain unclear and future studies are warranted. Green spaces and birth weight were not associated; thus, increased accessibility to green spaces does not explain the observed association with greenness.

In the second publication, hyperactivity/inattention and peer relationship problems were positively associated with increasing distances to urban green spaces in 10-year-old children in the city of Munich and its surrounding areas. When stratified by sex, the observed association with hyperactivity/inattention was only statistically significant among males. Children living further than 500 m away from any urban green space had more overall behavioural problems than those living within 500 m of an urban green space. Interestingly, behavioural problems were not associated with the distance to a forest or with residential surrounding greenness. Since we did not have information on green spaces' use, we were unable to provide verified explanations of the results of these additional analyses. Nevertheless, our findings suggest beneficial effects of living in close proximity to well-maintained green spaces on children's mental health, particularly, on hyperactivity and inattention symptoms and especially in boys.

We were the first to find an inverse association between objectively assessed residential greenness and BP in children in an observational study (the third publication). The observed association was not influenced by environmental stressors, such as ambient temperature and air pollution, noise annoyance, altitude and level of urbanisation. The association between greenness and BP is in line with the previous existing evidence from experimental studies and thus, with the psychoevolutionary theory of Ulrich (24). Contact with green environments, according to Ulrich, mitigates stress by activating the parasympathetic system (specifically, by decreasing BP). However, when stratified by study area, the associations were only significant in the urban Munich study area but null in the rural Wesel area. This result might indicate that children living in urbanised regions, which generally lack vegetation, might benefit more from high residential greenness than those from the rural areas.

2.4 Limitations

A detailed discussion of limitations has been given in the three publications. Here, the major limitations will be briefly summarised.

First of all, it was possible to conduct only cross-sectional analyses. Given the general lack of studies investigating the effects of greenness and green spaces on health (specifically, in children), the results should be interpreted cautiously. Causality cannot be inferred and the observed associations may be due to chance or residual confounding. Specifically, area-level socioeconomic status (SES) data were not available, and it could be a source of residual confounding, as more deprived neighbourhoods are usually less green.

Furthermore, there is a potential for attrition bias as families with a lower level of education and income were less likely to be initially recruited and to continue participating in the 10-year follow-up of the GINIplus and LISAplus cohorts. Therefore, as in the case with the Danish National Birth Cohort, children with a lower SES are underrepresented in the studies, and the generalizability of findings is questionable (37). Moreover, the effect of any self-selection bias on the associations cannot be excluded. That is, that parents from a higher SES are more likely to select living in greener neighbourhoods.

Residential greenness was objectively estimated by the common vegetation indicator NDVI. However, NDVI does not allow different types of vegetation to be distinguished and is sensitive to atmospheric effects, clouds and types of soil (34). Additionally, only few of Landsat 5 TM cloud-free satellite images to cover the study areas were available, which made difficult to obtain greenness for more alternative dates. Unfortunately, the information on time and activities spent outside in the neighbourhood were unavailable which might lead to exposure misclassification. Also, the information on quality characteristics of green spaces (e.g. accessibility to the public, perceived safety, availability of playgrounds, maintenance, and occurrence of organised events) and their use were unavailable, all of which could result in residual confounding.

3 Conclusion and outlook

This thesis supports the presumed beneficial effects of objectively measured satellite-derived access to green spaces and residential greenness on children's health. Greenness at maternal residential address was positively associated with the birth weight of newborns. Further, poor access to urban green spaces was associated with behavioural problems (especially, hyperactivity and inattention) in 10-year-old children. Moreover, I was the first to identify the association between residential greenness and BP in 10-year-old children in an observational study. However, in this novel emerging research area of environmental epidemiology, my thesis has a rather explorative role, and its results are descriptive. Despite of my attempts, I could only partially identify the underlying mechanisms leading to positive effects of residing in green environments.

In particular, among these potential biological pathways, ambient air pollution and questionnaire-derived physical activity do not appear to be influential factors in any of my three analyses, which might be due to insufficient data. However, I am planning to further investigate the potential mediating role of these factors using 15-year follow-up studies of the GINIplus and LISAplus birth cohorts with information on residential ambient air pollution and accelerometer-derived physical activity.

Moreover, the effects of increased social support and alleviation of mental fatigue and physiological stress deserve more attention by researchers. Mitigation of physiological stress through contact with green environments was partially confirmed by the finding of lower BP at greener residences in one of the analyses included in this thesis. Additionally, further investigation of potential effect modification of green spaces and greenness effects by urbanisation and SES, both individual and area-level, is needed. Strong effect modification of the association between greenness and birth weight by SES was identified within this thesis.

To summarise, this thesis' findings might not only be of scientific interest, partially covering an existing research gap, but could also be important for city planners and health policy makers. Investigating more health outcomes in association with different types of green exposure in different age groups and in different geographical settings, and especially with employment of a prospective study design, is warranted. Moreover, there is room for further improvement of the exposure assessment techniques, first of all, by incorporating not only accessibility, but also use of green spaces and residential greenness. Finally, future research should focus more on testing plausible biological mechanisms behind the health effects of green spaces and greenness.

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5 Paper 1: Greenness and Birth Weight
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Surrounding greenness and birth weight: Results from the GINIplus and LISAplus birth cohorts in Munich

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ABSTRACT

Aim: We investigated the association between surrounding greenness at the mother's residential address at the time of delivery and birth weight in two German birth cohorts and explored potential underlying hypotheses.
Methods: Complete data on 3203 newborns, recruited in Munich between 1996 and 1999, were available. Surrounding greenness was defined using the mean of the Normalized Difference Vegetation Index, which was derived from Landsat 5 TM satellite images.
Results: An interquartile increase of surrounding greenness in a 500-m buffer was associated with an average birth weight increase of 17.6 g (95% CI=0.5 to 34.6). The effect strengthened after individual adjustment for NO_2, PM2.5, distance to major road and population density. The strongest association was found for mothers with less than 10 years of school education. The results remained robust when additionally adjusted for noise or maternal stress during pregnancy. Neighbourhood green spaces were not associated with birth weight.
Conclusions: Surrounding greenness at the birth address was positively associated with birth weight in two birth cohorts in Munich. The mechanisms driving this association remain unclear and warrant further investigation.

1. Introduction

Positive associations between surrounding greenness and birth outcomes have been observed in three recent studies (Dadvand et al., 2012a, b; Donovan et al., 2011). The underlying mechanisms behind these associations are unclear. It has been hypothesised that higher surrounding greenness may increase physical activity and promote social interaction among pregnant women, as well as reduce their psychological stress and depression. Furthermore, areas with higher surrounding greenness are suspected of having lower air pollution and noise levels and may moderate ambient temperature. If one assumes surrounding greenness is a surrogate from neighbourhood green spaces and these have been used interchangeably in previous studies (Dadvand et al., 2012a, b), these same hypotheses could apply.

We aimed to assess the association between surrounding greenness at the mother's residential address at the time of delivery and the birth weight of newborns. We also explored potential underlying hypotheses for this association. Furthermore, in order to determine whether greenness may be acting as a surrogate for green spaces, we investigated whether neighbourhood green spaces are also associated with birth weight.

2. Materials and methods

2.1. Study population

The analyses were based on data collected within two ongoing German birth cohorts: the "**G**erman **I**nfant Study on the Influence

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of **N**utrition **I**ntervention **plus** Environmental and Genetic Influences on Allergy Development" (GINIplus) study and the "Influence of **L**ife-Style Factors on the Development of the **I**mmune **S**ystem and **A**llergies in East and West Germany **plus** the Influence of Traffic Emissions and Genetics" study (LISAplus). Detailed descriptions of these cohorts have been published elsewhere (Heinrich et al., 2002; von Berg et al., 2003, 2013; Zutavern et al., 2006). Both studies had a similar study design and recruited healthy full-term neonates (gestational age ≥ 37 weeks) with a normal birth weight (>2500 g). GINIplus participants were recruited in the cities of Munich and Wesel between 1995 and 1998 ($n=5991$). LISAplus participants were recruited in the cities of Munich, Wesel, Bad Honnef and Leipzig between 1997 and 1999 ($n=3097$). Information on the home address, socioeconomic characteristics of parents, and lifestyle factors was collected by parent-completed questionnaires administered at birth. From 1996 onwards, the weight of the neonates at birth was measured by physicians during a clinical examination. Children born in 1995 were not weighed and are thus excluded from all analyses ($n=453$). Both studies were approved by the local ethics committees (Bavarian Board of Physicians, University of Leipzig and Board of Physicians of North-Rhine-Westphalia) and informed consent was obtained from all parents of participants.

We restricted our analyses to participants recruited in Munich obstetric clinics and whose place of residence at birth was in Bavaria, the state in which Munich lies (Supplementary Fig. 1). Further inclusion criteria included available information on the birth address, birth weight and other covariates. We excluded non-singleton births, as the overall pattern of foetal growth is slower for twins compared to singletons (Min et al., 2000). Ultimately, the number of study participants in our analyses was 3203 ($n=2022$ from GINIplus and $n=1181$ from LISAplus).

2.2. Definitions of green exposure

2.2.1. Surrounding greenness

To determine surrounding greenness, we used the Normalized Difference Vegetation Index (NDVI), which is derived from Landsat 5 Thematic Mapper (TM) satellite images available at a spatial resolution of 30 m from the Global Visualisation Viewer from the U.S. Geological Survey ⟨http://earthexplorer.usgs.gov/⟩.

NDVI is an indicator of green biomass density and its calculation is based on the difference of surface reflectance in visible (from 0.4 μm to 0.7 μm) and near-infrared (from 0.7 μm to 1.1 μm) wavelengths. Values of NDVI range from −1 to 1 with values close to 1 indicating high density of green leaves and values close to zero referring to barren areas of rock, sand or snow. Negative values correspond to water (Weier and Herring, 2011).

As there were no cloud-free images of Bavaria available for the years 1996–1999, when the study participants were recruited, we chose images for the year closest to the time of recruitment (2003). We assumed that the spatial contrasts of greenness remained stable, as has been shown by Dadvand et al. (2012b). As approximately two thirds of the residences were outside of the city of Munich (up to 100 km away from the city centre), the study area included two administrative regions of Bavaria state – Upper Bavaria and Swabia – with a total land area of 27,521.66 km^2 (Supplementary Fig. 1). We downloaded satellite images from the 14th of July and the 24th of August and merged them (data covering the entire study territory were not available for a single day). Based on these images, NDVI values were calculated at a resolution of 30 m × 30 m (Fig. 1a). Negative values of NDVI, as they normally correspond to water, were excluded before further calculation as water is not hypothesised to have a negative effect on birth weight.

As a proxy for surrounding greenness, we calculated mean values of NDVI in circular 100-m, 250-m, 500-m and 800-m buffers around the place of residence of each participant at the time of birth. These buffers were selected in order to generate results comparable to previous studies (Dadvand et al., 2012a, b; Donovan et al., 2011).

Data management and calculations of NDVI were done in ArcGIS 10.0 Geographical Information System (GIS) (ESRI, Redlands, CA) and Geospatial Modelling Environment (GME) (Spatial Ecology LLC).

2.2.2. Neighbourhood green space

For the same addresses, we also calculated the area of neighbourhood green space ((i) forests, (ii) parks and (iii) forests and parks) in a 500-m buffer (Fig. 1b). Data for the calculation of neighbourhood green space were obtained from the local Bavarian

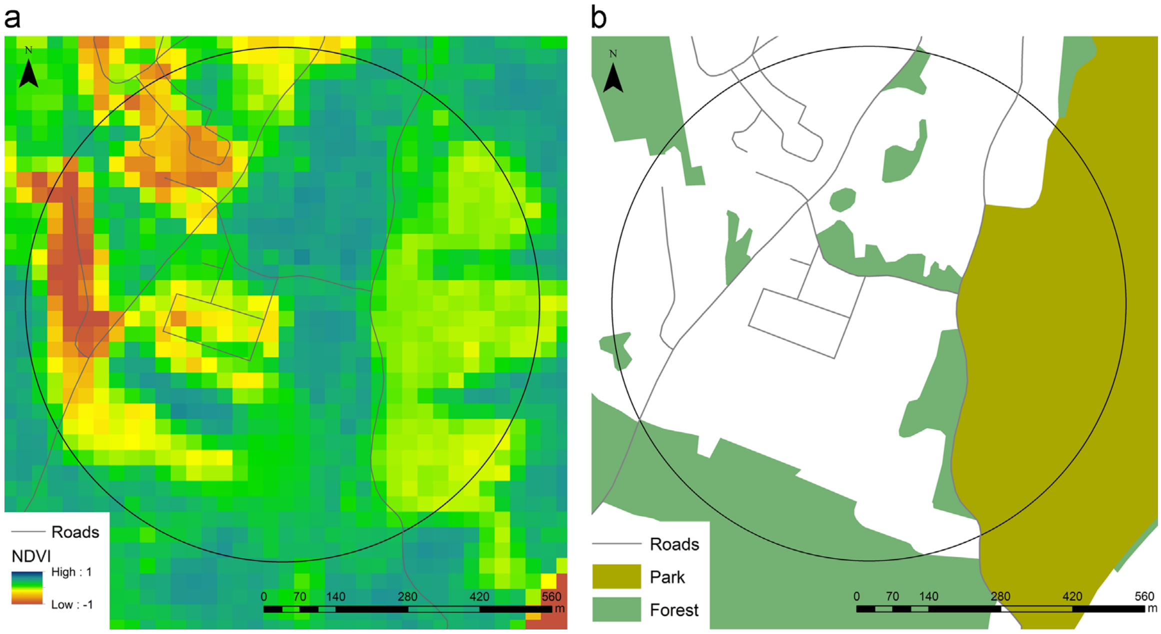

Fig. 1. Greenness (a) and green spaces (b) in a buffer of 500 m around the same residence.

land use dataset (vector with spatial resolution of <5 m) from the Bavarian Survey Office for the year 2008.

2.3. Main analyses

Associations between surrounding greenness in each buffer and birth weight were assessed using multivariable linear regression. Effect estimates represent the change in birth weight in grams per one interquartile range (IQR) increase in NDVI, with corresponding 95% confidence intervals (CIs).

All models were adjusted for study (GINIplus/LISAplus), year of birth (1996/1997/1998/1999), season of birth (winter/spring/summer/autumn), infant sex (male/female), maternal age (continuous), maternal educational level (low for <10/medium for 10/and high for >10 years of school, according to the German education system) and maternal smoking during pregnancy (yes/no) and are here-on referred to as the "main models".

We repeated all analyses using neighbourhood green spaces as the exposure instead of surrounding greenness.

Statistical analyses were performed in SAS (version 9.2; SAS Institute Inc., Cary, NC, USA).

2.4. Further analyses

2.4.1. Surrounding greenness, air pollution and birth weight

To explore the potential role of air pollution on the association of interest, we additionally adjusted our main models for: (i) nitrogen dioxide (NO_2) and (ii) particles with an aerodynamic diameter below 2.5 μm ($PM_{2.5}$), both modelled at the residential address at birth. Exposure to NO_2 and $PM_{2.5}$ was estimated within the ESCAPE study (European Study of Cohorts for Air Pollution Effects, 〈http://www.escapeproject.eu/〉 in 2008–2009 by land use regression (LUR) models that predicted 86% and 78% of variation in the levels of these air pollutants, respectively. A more detailed description has been given elsewhere (Beelen et al., 2013; Cyrys et al., 2012, Eeftens et al., 2012a, b).

2.4.2. Surrounding greenness, noise and birth weight

We additionally adjusted our main models for long-term road traffic noise exposure. The noise data are based on the Munich noise map created for the year 2007, as described in Birk et al. (2011) and Tiesler et al. (2013). The weighted day-evening-night equivalent noise level of the most exposed façade (L_{den}) of the participant's birth address was chosen as the measure of noise exposure. These data were available for the city of Munich only ($n=1817$ participants).

2.4.3. Surrounding greenness, distance to major road and birth weight

As busy roads are often used as a proxy for traffic noise and air pollution, we adjusted our main models for the distance to the nearest major road from the birth address of the participants. Major roads were defined as street segments with a daily traffic volume of more than 5000 vehicles per day. For these calculations, we used road data from the year 2005 (vector with spatial resolution of <5 m).

2.4.4. Surrounding greenness, population density and birth weight

One of our assumptions was that a higher surrounding greenness might reflect a lower level of urbanisation. To test this hypothesis, we adjusted our main models for neighbourhood population density derived for 100-m, 250-m, 500-m and 800-m buffers to match the buffer size of the greenness variable. Data for these calculations – a raster with a spatial resolution of 125 m – were obtained from the WiGeoGIS population density dataset for the year 2008.

2.4.5. Impact of maternal characteristics on birth weight

As some variables that could potentially influence the association between greenness and birth weight were collected only in the LISAplus cohort, we conducted a sensitivity analysis within this cohort ($n=1132$). The main models were adjusted for the mother's pregestational body mass index (BMI), as well as weight gain and ingestion of alcohol during pregnancy.

As it was hypothesised that greenness could relieve maternal stress during pregnancy (Dadvand et al., 2012a, b; Donovan et al., 2011), we also additionally adjusted the main models for the presence of stress-related factors during pregnancy. A detailed description of how stress-related factors were defined is provided in Sausenthaler et al. (2009). Briefly, having two or more of the 12 factors assessed (unwanted pregnancy, psychological stress, social stress, bleeding before and after 28 weeks' gestation, placental insufficiency, premature labour, anaemia, positive indirect Coombs test, risk based on other serological findings, hypertension and proteinuria) was defined as having stress-related factors during pregnancy. These data were obtained from the "Mutterpass", a maternity certificate routinely completed in obstetrical practices in Germany.

As there is some evidence that the beneficial effects of green exposure may differ by socioeconomic status, we stratified our analyses by maternal educational level, as has been done previously (Dadvand et al., 2012a, b).

3. Results

The socio-demographic characteristics and exposure levels of study participants are presented in Table 1. The average birth weight was 3431 g. The mean values of greenness (NDVI) in the 100-m, 250-m, 500-m and 800-m buffers around the residential address at birth were 0.304, 0.318, 0.329, and 0.337, respectively, and were moderately to strongly correlated (Pearson's correlation coefficients ranged from 0.71 to 0.96).

In bivariate analyses (Supplementary Table 1), NDVI was positively associated with the distance to the nearest major road and inversely associated with maternal smoking during pregnancy, maternal NO_2 and $PM_{2.5}$ exposure and population density.

As shown in Table 2, higher surrounding greenness in a 500-m buffer was associated with higher birth weight in both crude and adjusted models. For smaller (100-m and 250-m) and larger (800-m) buffer sizes, estimates were in the same direction but not statistically significant.

The effect of greenness in a 500-m buffer on birth weight remained statistically significant after additionally adjusting the main models for either $PM_{2.5}$, NO_2, distance to the nearest major road or population density. Moreover, after the main models were adjusted for NO_2, the associations with greenness in 250-m and 800-m buffers were statistically significant. Similarly, after adjustment for $PM_{2.5}$, the association with greenness in a 250-m buffer was significant (Table 2). Associations between greenness for all buffers and birth weight were attenuated and no longer significant when the analysis was restricted to participants living in the city of Munich (change in birth weight per one IQR increase in NDVI in a 500-m buffer was 11.5 g (95% confidence interval (CI) $= -13.1$ to 36.1)), but were not further attenuated after additional adjustment for noise (Table 2). When the main models were adjusted for the distance to the nearest major road, the results were very close to those obtained in the NO_2- and $PM_{2.5}$-adjusted models (Table 2). The strongest association between greenness and birth weight was

Table 1
Characteristics of the study participants.

Variable	Total n (%) or mean ± SD		
	GINIplus	LISAplus	All
No. of participants	2022	1181	3203
Birth weight (g)	3431.5 ± 431.2	3429.5 ± 409.4	3430.8 ± 423.2
Sex			
Male	1040 (51.4)	619 (52.4)	1659 (51.8)
Female	982 (48.6)	562 (47.6)	1544 (48.2)
Year of birth			
1996	902 (44.6)	–	902 (28.2)
1997	1119 (55.3)	–	1119 (34.9)
1998	1 (0.1)	1107 (93.7)	1108 (34.6)
1999	–	74 (6.3)	74 (2.3)
Season of birth			
Winter	551 (27.3)	265 (22.4)	816 (25.5)
Spring	594 (29.4)	302 (25.6)	896 (28.0)
Summer	466 (23.1)	319 (27.0)	785 (24.5)
Autumn	411 (20.3)	295 (25.0)	706 (22.0)
Maternal age (years)	31.7 ± 4.3	32.7 ± 4.0	32.1 ± 4.2
Maternal level of education[a]			
Low	238 (11.8)	77 (6.5)	315 (9.8)
Medium	607 (30.0)	324 (27.4)	931 (29.1)
High	1177 (58.2)	780 (66.1)	1957 (61.1)
Maternal smoking during pregnancy			
Yes	265 (13.1)	165 (14.0)	430 (13.4)
No	1757 (86.9)	1016 (86.0)	2773 (86.6)
NDVI[b]			
100-m buffer	0.303 ± 0.098	0.305 ± 0.102	0.304 ± 0.099
250-m buffer	0.316 ± 0.088	0.321 ± 0.094	0.318 ± 0.090
500-m buffer	0.327 ± 0.083	0.333 ± 0.089	0.329 ± 0.086
800-m buffer	0.334 ± 0.082	0.343 ± 0.088	0.337 ± 0.084
Green spaces in a 500-m buffer (km^2)			
Forests	0.028 ± 0.072	0.038 ± 0.090	0.031 ± 0.079
Parks	0.032 ± 0.050	0.034 ± 0.056	0.032 ± 0.053
Forests and parks	0.060 ± 0.080	0.071 ± 0.096	0.064 ± 0.087
NO_2 concentration at the residential address at birth (μg/m³)	22.0 ± 6.2	21.7 ± 6.0	21.9 ± 6.1
$PM_{2.5}$ concentration at the residential address at birth (μg/m³)	13.4 ± 1.0	13.4 ± 1.0	13.4 ± 1.0
Noise at the residential address at birth (dB(A))[c]	53.8 ± 9.0	53.0 ± 8.6	53.5 ± 8.9
Distance of the residential address at birth to the nearest major road[d] (m)	344.9 ± 635.1	320.1 ± 503.0	335.8 ± 589.9
Population density around the residential address at birth (1000 people/km^2)			
100-m buffer	9.79 ± 7.32	9.35 ± 7.31	9.62 ± 7.32
250-m buffer	7.95 ± 6.11	7.67 ± 6.21	7.85 ± 6.14
500-m buffer	6.51 ± 5.26	6.30 ± 5.25	6.43 ± 5.25
800-m buffer	5.67 ± 4.71	5.44 ± 4.66	5.59 ± 4.69

[a] Defined as low for < 10, medium for 10, and high for > 10 years of school, according to the German education system.
[b] Normalized Difference Vegetation Index.
[c] Data were available only for the city of Munich (n = 1817).
[d] Defined as a street segment with a daily traffic volume > 5000 vehicles per day.

observed when the main models were additionally adjusted for population density; the effect of surrounding greenness on birth weight doubled and was statistically significant for all buffers (Table 2). Population density was also independently significantly associated with birth weight in all models.

When the main models were restricted to LISAplus participants only, the size and direction of the effect estimates were similar but no longer significant (Supplementary Table 3). These effect estimates increased when the models were adjusted for the mother's pregestational BMI, as well as weight gain and ingestion of alcohol during pregnancy (Supplementary Table 3). After adjustment for the presence of stress-related factors during pregnancy, the effect estimates did not change (Supplementary Table 3).

In stratified analyses, the association between birth weight and surrounding greenness was strongest for children born to mothers with less than 10 years of school and was not significant for children born to mothers with at least 10 years of school (Table 3).

There was no link between neighbourhood green spaces in a 500-m buffer and birth weight in any of the models tested (Supplementary Table 2). Moreover, greenness and neighbourhood green spaces were only weakly correlated (Spearman correlation coefficient r_s = 0.33).

4. Discussion

4.1. Key findings

Birth weight was positively associated with surrounding greenness in a 500-m buffer around the residence at birth, but not with neighbourhood green spaces in this same buffer. After adjustment for NO_2, $PM_{2.5}$ or distance to the nearest major road, the association with greenness strengthened and became significant for other buffer sizes. The effect of surrounding greenness on birth weight

Table 2
Change of average birth weight (g) and corresponding 95% confidence intervals per one interquartile range[a] increase in NDVI around the residential address at birth.

Model	NDVI			
	100-m buffer	250-m buffer	500-m buffer	800-m buffer
Unadjusted	12.5 (−5.1, 30.1)	17.2 (−0.2, 34.5)	19.9 (2.6, 37.1)*	19.0 (0.2, 37.8)*
Adjusted[b]	12.2 (−5.2, 29.6)	16.0 (−1.1, 33.2)	17.6 (0.5, 34.6)*	16.5 (−2.2, 35.1)
NO_2-adjusted[c]	16.2 (−3.9, 36.2)	21.4 (1.5, 41.2)*	23.6 (3.8, 43.3)*	22.5 (0.7, 44.3)*
$PM_{2.5}$-adjusted[d]	14.8 (−3.1, 32.8)	18.3 (0.7, 35.8)*	19.3 (1.9, 36.6)*	17.9 (−0.9, 36.7)
Noise-adjusted[e]	5.4 (−18.0, 28.7)[f]	5.9 (−18.0, 29.7)[f]	11.5 (−13.2, 36.1)[f]	13.1 (−14.7, 40.8)[f]
Adjusted for proximity to the major road[g]	15.0 (−2.9, 33.0)	19.7 (1.8, 37.5)*	21.8 (3.9, 39.7)*	21.1 (1.5, 40.8)*
Adjusted for population density[h]	22.8 (0.8, 44.8)*	31.9 (8.7, 55.1)*	38.3 (14.9, 61.6)*	36.0 (10.5, 61.6)*

[a] 0.119 for 100-m buffer, 0.107 for 250-m buffer, 0.101 for 500-m buffer, and 0.108 for 800-m buffer.
[b] Adjusted for study, year of birth, season of birth, sex, maternal age, maternal education level, and maternal smoking during pregnancy.
[c] Adjusted model + NO_2 concentration at the residential address at birth.
[d] Adjusted model + $PM_{2.5}$ concentration at the residential address at birth.
[e] Adjusted model + road traffic noise at the residential address at birth; noise data were only available for the city of Munich ($n = 1817$).
[f] The results of the adjusted models for the city of Munich without adjustment for noise: 100-m buffer 5.8 (−17.5, 29.1), 250-m buffer 6.0 (−17.8, 29.8), 500-m buffer 11.5 (−13.1, 36.1), and 800-m buffer 13.1 (−14.7, 40.9).
[g] Adjusted model + proximity of the residential address at birth to the nearest major road.
[h] Adjusted model + population density around the residential address at birth.
* $p < 0.05$.

Table 3
Change of average birth weight (g) and corresponding 95% confidence intervals per one interquartile range[a] increase in NDVI around the residential address at birth stratified by maternal education level[b].

Education level of mother[c]	NDVI			
	100-m buffer	250-m buffer	500-m buffer	800-m buffer
Low ($n = 315$)	46.2 (−14.4, 106.8)	55.8 (−2.0, 113.7)	58.2 (2.0, 114.4)*	52.1 (−9.7, 114.0)
Medium ($n = 931$)	4.7 (−29.7, 39.1)	13.0 (−22.1, 48.2)	20.4 (−14.6, 55.3)	19.4 (−18.6, 57.3)
High ($n = 1957$)	11.5 (−9.7, 32.6)	11.9 (−8.8, 32.6)	10.4 (−10.3, 31.1)	10.0 (−12.7, 32.6)

[a] 0.119 for 100-m buffer, 0.107 for 250-m buffer, 0.101 for 500-m buffer, and 0.108 for 800-m buffer.
[b] Adjusted for study, year of birth, season of birth, sex, maternal age, and maternal smoking during pregnancy.
[c] Defined as low for < 10, medium for 10, and high for > 10 years of school, according to the German education system.
* $p < 0.05$.

doubled after adjustment for population density. Associations were attenuated after restricting the study population to the city of Munich, but were not further attenuated after additional adjustment for noise. Including maternal stress during pregnancy in the models (LISAplus cohort only) also did not attenuate the observed associations. After stratifying the analyses by maternal educational level, the association between greenness and birth weight was only significant for mothers who attended school for less than 10 years.

4.2. Comparison with previous studies

There are only three studies that have investigated the impact of green exposure on birth outcomes, one conducted in the USA (Donovan et al., 2011) and two in Spain (Dadvand et al., 2012a, b). Overall, our findings of a positive association between birth weight and higher green exposure are in line with these previous studies, although certain differences should be highlighted. In the current study, preterm births and newborns with low birth weight were not included in the GINIplus and LISAplus cohorts by design. Donovan et al. (2011), who used different exposure and outcome definitions than in the current study, observed a reduction in the risk of small for gestational age (SGA) with increasing residential tree-canopy cover, but only for a 50-m buffer. Results for 100-m and 200-m buffers were null. Dadvand et al. (2012b) reported positive associations between birth weight and NDVI in 100-m, 250-m and 500-m buffers and associations were strongest for the 500-m buffer. In our study, the association was also most consistent for the 500-m buffer. A possible explanation for this observation is that a 500-m distance may be an average walkable distance around the home for pregnant women (Dadvand et al., 2012a). As observed in the two Spanish studies and in our study, associations were robust to the adjustment for NO_2 and distance to the nearest major road. But in our study, this adjustment strengthened the association, whereas in the Spanish study (Dadvand et al., 2012b), it was weakened.

Dadvand et al. (2012a) observed a beneficial effect of surrounding greenness on birth weight, but only among those with low education levels. In the groups' next study (Dadvand et al., 2012b), they reported that the association between greenness and birth weight was most pronounced in the two lowest socioeconomic strata. We found similar results.

It is challenging to compare our findings on neighbourhood green spaces with those reported by Donovan et al. (2011) and Dadvand et al. (2012a) as we used different definitions aimed at assessing different study questions. In the current study, we used the area of green space around the home address, whereas in the previous studies, the linear distance to green spaces from the home address was used. Our assumption was that the area of green spaces around the residence is more comparable to average NDVI in a given buffer than the linear distance to the nearest green space. While these two studies reported a link between green spaces and birth outcomes, we were unable to replicate this finding.

As these studies did not include $PM_{2.5}$, noise, population density and maternal stress in their analyses, we are unable to compare our findings with theirs.

4.3. Possible interpretations

In previous studies, Donovan et al. (2011) and Dadvand et al. (2012a, b) speculated about the potential mechanisms behind the positive effect of surrounding greenness on birth weight. Some of these potential hypotheses (e.g. increased physical activity among pregnant women) are based on the assumption that higher greenness is a surrogate for more green spaces. In our study, greenness and neighbourhood green spaces were only weakly correlated and neighbourhood green spaces were not associated with birth weight in any of our analyses. It should be noted that surrounding greenness and neighbourhood green spaces reflect different types of green exposure and therefore their effects might be different. While greenness represents the density of green biomass, green spaces represent access to parks, forests, gardens etc. Fig. 1 demonstrates how different these two calculated green exposures might be at the same place of residence. Thus, caution is required when comparing and contrasting these two definitions of green exposure.

Maternal exposure to various outdoor air pollutants has been shown to affect birth weight (Sapkota et al., 2012; Srám et al., 2005; Govarts et al., 2012). Thus, air pollution levels have been proposed as a candidate mechanism to explain the observed effect of greenness on birth weight (Dadvand et al., 2012a, b). In our analyses, we observed an inverse association between greenness and maternal exposure to NO_2 and $PM_{2.5}$. Moreover, greenness was positively associated with the distance to the nearest major road, which is widely used as a proxy for transport-related air and noise pollution. When we adjusted the main models for air pollutants or the distance to the nearest major road, the estimates with greenness became larger, whereas similar analysis in the study by Dadvand et al. (2012b) attenuated the results. Our results thus indicate that air pollution levels are indeed lower in greener surroundings, but they do not explain the positive effect of greenness on birth weight. As the interrelationship between greenness, air pollution and birth weight in our analysis differ from the results of Dadvand et al. (2012b), future studies are needed to further investigate these associations.

Dadvand et al. (2012a, b) also proposed that lower noise exposure in areas with higher greenness may be the underlying mechanism. The impact of traffic noise at maternal residences on birth weight has not yet been studied. However, an association between maternal exposure to noise from other sources and birth weight has been investigated in several studies. According to the recent review by Hohmann et al. (2013), occupational and aircraft noise exposure during pregnancy was not associated with birth weight in six out of eight European studies. In our analysis, adjusting the models restricted to the city of Munich for noise did not alter the effect estimates. Moreover, there was no correlation between greenness and noise levels. Therefore, our results indicate that lower noise levels in greener surroundings are unlikely to be a possible explanation for the observed effects of greenness.

We are the first to investigate the interrelation between greenness, population density (as a measure of urbanisation) and birth weight. Surprisingly, the effect estimates doubled after the models were adjusted for population density. Moreover, population density was significantly positively associated with birth weight in all models. This observation suggests that population density probably independently affects birth weight. In addition to population density, we anticipate that other neighbourhood characteristics are also likely associated with birth outcomes and these factors warrant further investigation.

A more natural neighbourhood has been shown to improve psychological health (Bowler et al., 2010; Annerstedt et al., 2012; van den Berg et al., 2010; Stigsdotter et al., 2010). The effect of maternal stress and depression on low birth weight has also been demonstrated in many studies (e.g., Nkansah-Amankra et al., 2010; Borders et al., 2007; Grote et al., 2010). As the role of greenness exposure on maternal stress relief seemed to be a promising candidate mechanism to explain the observed associations, we conducted a sensitivity analysis for LISAplus participants for whom data on maternal stress-related factors during pregnancy were available. We observed no decrease in the effect of greenness in this sub-population when the models were adjusted for stress.

In line with what was observed by Dadvand et al. (2012a, b), we discovered the strongest beneficial effect of surrounding greenness among mothers with the lowest level of education. There are several hypotheses in the literature as to why health benefits from green exposure are unequal among people with different socioeconomic statuses. In particular, people with lower socioeconomic statuses tend to have lower mobility, and thus are likely to spend more time close to their residences and consequently reap the benefits of the surrounding areas with higher NDVI (Dadvand et al., 2012b; Maas et al., 2009).

Ultimately, despite testing several hypotheses for the association between greenness and birth weight, the mechanisms driving this apparent consistent association remain unknown.

4.4. Strengths and limitations

The main strength of our study is the large number of participants. Moreover, we were able to control for many covariates and perform several sensitivity analyses to examine underlying mechanisms.

However, some limitations should be stated. The main limitation is a cross-sectional design of our analyses, thus, causal relationships cannot be inferred. Another big limitation is a potential for selection bias, as pregnant women residing outside Munich who decide to deliver in the city of Munich might have different characteristics than those who decide to deliver at local obstetrics clinics (e.g. fear that the small hospitals are not well enough equipped if there are complications during delivery or if a child has a serious problem). For our study, we used the most common vegetation index NDVI, which on the one hand, is an objective measure of greenness, but on the other hand, does not distinguish different types of vegetation, is sensitive to atmospheric effects, clouds and soils (Weier and Herring, 2011). Also, Landsat 5 TM satellite images exist at resolution of 30 m which might be not precise enough. Another limitation is that cloud-free satellite images, used to derive the NDVI values, were unavailable for the years when the study participants were born and recruited (1996–1999). In this study, we assumed that spatial contrasts of greenness remained stable, as was shown in the study by Dadvand et al. (2012b). Also, images to cover the entire study territory were not available for the same day. Thus, we used two images taken in July and one taken in August. However, as only two addresses lie in the area for which the August image was used, the results should be only minimally affected. Another limitation is that air pollution measurements were conducted up to 13 years after delivery. However, several studies have demonstrated that the spatial contrast of air pollution remain stable over time to over 10 years (Eeftens et al., 2011; Cesaroni et al., 2012; Gulliver et al., 2013; Wang et al., 2013). Therefore, we infer that, although air pollution levels might have decreased between the time points of delivery and air pollution measurements, the assessment of spatial contrasts of air pollution concentrations is valid. Similarly, road traffic noise map for the inner city Munich was modelled for the year 2007, but we assumed that noise contrasts remained stable, as there were no major changes in the local road network. Additionally, noise assessment was conducted for the city of Munich only and does not cover all the study area. One further limitation is that our exposure assessment was assigned to the home address at the time of delivery, which might lead to exposure misclassification. For instance, residential mobility rates during pregnancy were shown to be up to 32% (Bell and Belanger, 2012). Finally, we were unable to control for area level socioeconomic indicators and the time spent outside in the neighbourhood during pregnancy, which might be sources of residual confounding.

5. Conclusion

We found a positive association between surrounding greenness at the home residence and birth weight, but not between neighbourhood green spaces and birth weight. The effect of greenness was most pronounced for children born to mothers with lower levels of education. The mechanisms underlying the discovered association remain unclear and future studies are warranted.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.healthplace.2013.12.001.

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Paper 1: Supplementary Material

Supplementary Table 1. Bivariate associations between surrounding greenness in a buffer of 500 m and characteristics of study participants.

Variable	NDVI [a] (mean ± SD)	*p*-value[b]
Birth weight (g)[c]		0.07
< 3,240	0.324 ± 0.086	
3,240 – 3,600	0.331 ± 0.085	
> 3,600	0.332 ± 0.086	
Sex		0.20
Male	0.331 ± 0.087	
Female	0.327 ± 0.084	
Year of birth		0.0003
1996	0.319 ± 0.085	
1997	0.333 ± 0.081	
1998	0.333 ± 0.089	
1999	0.329 ± 0.096	
Season of birth		0.82
Winter	0.330 ± 0.084	
Spring	0.329 ± 0.084	
Summer	0.330 ± 0.090	
Autumn	0.327 ± 0.085	
Maternal age (years)[c]		0.13
< 31	0.325 ± 0.083	
31 - 33	0.329 ± 0.085	
> 33	0.333 ± 0.089	
Maternal level of education[d]		0.57
Low	0.326 ± 0.086	
Medium	0.331 ± 0.078	
High	0.328 ± 0.089	
Maternal smoking during pregnancy		<.0001
Yes	0.315 ± 0.084	
No	0.331 ± 0.086	
NO_2 concentration at the residential address at birth ($\mu g/m^3$)[c]		<.0001
< 18.4	0.370 ± 0.084	
18.4 – 23.8	0.345 ± 0.065	
> 23.8	0.273 ± 0.075	
$PM_{2.5}$ concentration at the residential address at birth ($\mu g/m^3$)[c]		<.0001
< 13.0	0.342 ± 0.096	
13.0 – 13.8	0.340 ± 0.081	
> 18.3	0.306 ± 0.074	
Road traffic noise at the residential address at birth (dB(A))[c,e]		<.0001
< 48.9	0.293 ± 0.090	
48.9 – 55.2	0.314 ± 0.071	
> 55.2	0.302 ± 0.079	
Proximity of the residential address at birth to the nearest major road[f] (m)[c]		<.0001
< 112.2	0.306 ± 0.082	
112.2 – 282.3	0.316 ± 0.081	
> 282.3	0.365 ± 0.082	

Population density around the residential address at birth in a 500-m buffer (1000 people/m²)[c]		<.0001
< 3.65	0.387 ± 0.085	
3.65 – 6.54	0.337 ± 0.052	
> 6.54	0.264 ± 0.066	

[a]Normalized Difference Vegetation Index.
[b]Two-tailed unpaired Student's *t*-test or one-way ANOVA test.
[c]Categorised into tertiles.
[d]Defined as low for < 10, medium for 10, and high for > 10 years of school, according to the German education system.
[e]Data only available for the city of Munich (n = 1,817).
[f]Defined as a street segment with a daily traffic volume of more than 5,000 vehicles per day.

Supplementary Table 2. Change of average birth weight (g) and corresponding 95 % confidence intervals per one interquarile range[a] increase in green spaces in a 500-m buffer around the residential address at birth.

Model	Green spaces		
	Forests	Parks	Forests and parks
Unadjusted	0.5 (-2.2, 3.2)	1.2 (-10.3, 12.8)	3.0 (-10.0, 16.0)
Adjusted[b]	0.3 (-2.4, 2.9)	1.0 (-10.4, 12.4)	1.8 (-11.0, 14.7)

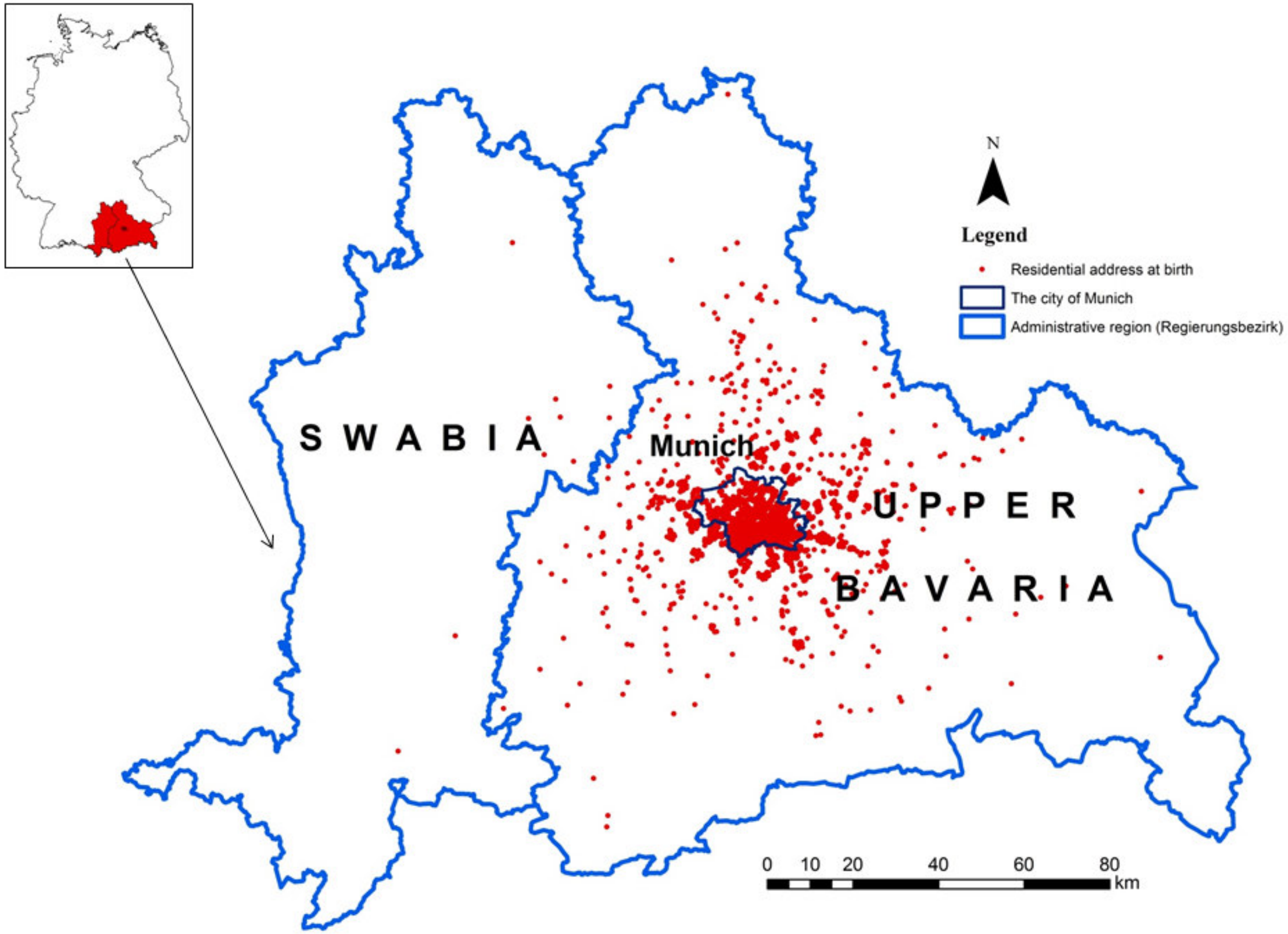
[a]14,662.8 m² for forests, 41,503.1 m² for parks, and 76,920.5 m² for forests and parks combined.

[b]Adjusted for study, year of birth, season of birth, sex, maternal age, maternal education level, and maternal smoking during pregnancy.

Supplementary Table 3. Change of average birth weight (g) and corresponding 95 % confidence intervals per 1-IQR[a] increase in NDVI around the residential address at birth; results for the LISAplus cohort.

Model	NDVI			
	100-m buffer	250-m buffer	500-m buffer	800-m buffer
Adjusted [b] (*n* = 1,132)	5.9 (-21.8, 33.6)	12.1 (-14.7, 38.8)	15.9 (-10.7, 42.5)	12.7 (-16.3, 41.6)
Additionally adjusted 1[c] (*n* = 1,132)	12.0 (-14.6, 38.6)	16.1 (-9.5, 41.8)	20.1 (-5.4, 45.6)	16.8 (-11.0, 44.6)
Adjusted (*n* = 1,147)	8.3 (-19.1, 35.6)	13.5 (-13.5, 40.0)	17.5 (-9.0, 44.0)	15.1 (-13.8, 43.9)
Additionally adjusted 2[d] (*n* = 1,147)	8.9 (-18.4, 36.2)	13.9 (-12.6, 40.4)	17.7 (-8.7, 44.2)	15.4 (-13.4, 44.2)

[a]0.119 for 100-m buffer, 0.107 for 250-m buffer, 0.101 for 500-m buffer, and 0.108 for 800-m buffer.
[b]Adjusted for study, year of birth, season of birth, sex, maternal age, maternal educational level, and maternal smoking during pregnancy
[c]Adjusted model + mother’s pre-gestational BMI, weight gain during pregnancy, and ingestion of alcohol during pregnancy.
[d]Adjusted model + presence of stress-related maternal factors during pregnancy.



Supplementary Figure 1. Map of the study area in Germany and spatial distribution of the study participants.

6 Paper 2: Access to Green Spaces and Behavioural Problems in Children
(Markevych et al. Environment International, 2014)

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Access to urban green spaces and behavioural problems in children: Results from the GINIplus and LISAplus studies

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ABSTRACT

Aim: We investigated whether objectively measured access to urban green spaces is associated with behavioural problems in 10-year old children living in Munich and its surrounding areas.
Methods: Behavioural problems were assessed in the GINIplus and LISAplus 10-year follow-up between 2006 and 2009 using the Strengths and Difficulties Questionnaire. Access to green spaces was defined using the distance from a child's residence to the nearest urban green space. Associations between access to urban green spaces and behavioural problems were assessed using proportional odds and logistic regression models in 1932 children with complete exposure, outcome and covariate data.
Results: The distance between a child's residence and the nearest urban green space was positively associated with the odds of hyperactivity/inattention, especially among children with abnormal values compared to children with borderline or normal values (odds ratio (OR) = 1.20 (95% confidence interval (CI) = 1.01–1.42) per 500 m increase in distance). When stratified by sex, this association was only statistically significant among males. Children living further than 500 m away from urban green spaces had more overall behavioural problems than those living within 500 m of urban green spaces (proportional OR = 1.41 (95% CI = 1.06–1.87)). Behavioural problems were not associated with the distance to forests or with residential surrounding greenness.
Conclusion: Poor access to urban green spaces was associated with behavioural problems in 10-year old children. Results were most consistent with hyperactivity/inattention problems.

1. Introduction

Currently, more than half of the world's population lives in urban settings (United Nations, 2011). An increasing number of children grow up in cities and often have limited access to green spaces. The effects of urbanisation on the well-being of children have not been adequately investigated. Further insight into the effects of urban green space access on children's health is needed to inform efficient city planning and the development of effective health policies (Kyttä et al., 2012; Lee and Maheswaran, 2010).

Green spaces appear to have positive effects on human psychological health (Bowler et al., 2010; Lee and Maheswaran, 2010). However, with only a few exceptions, most studies examining associations between green spaces and mental health have been conducted among adults (Bowler et al., 2010; Lee and Maheswaran, 2010). Moreover, objective measurements of green space access have rarely been used in these studies (Annerstedt et al., 2012; Kyttä et al., 2012; Lee and Maheswaran, 2010; Stigsdotter et al., 2010).

Several hypotheses have been proposed to explain how green spaces may have a beneficial effect on mental health and well-being. There is mounting evidence supporting the restorative and stress reductive effects of green spaces (Fan et al., 2011). Better access to green spaces is also hypothesised to promote physical activity, which

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could ultimately lead to improved mental functioning (Fan et al., 2011; Lee and Maheswaran, 2010). Finally, green spaces might also improve psychological health by encouraging the development of social contacts (Maas et al., 2009).

We investigated whether objectively measured access to urban green spaces was associated with behavioural problems in 10-year old children living in Munich and its surrounding areas.

2. Materials and methods

2.1. Study population

The "German Infant Study on the Influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development" (GINIplus) study and the "Influence of Life-Style Factors on the Development of the Immune System and Allergies in East and West Germany plus the Influence of Traffic Emissions and Genetics" study (LISAplus) are ongoing population-based birth cohorts. Both cohorts have a similar study design and recruited healthy full-term neonates with a normal birth weight. GINIplus participants were recruited in the cities of Munich ($n = 2949$) and Wesel ($n = 3042$) between 1995 and 1998. This cohort consists of two study groups: one is an observation group and the second includes a nutritional intervention conducted during the first four months of life, in which a randomised, double-blind controlled trial compared the effect of three hydrolysed formulas versus cow's milk formula on allergy development. Newborns with a family history of allergy were selected for the intervention group. Participants with a negative family history or a positive family history but who declined to participate in the intervention trial were included in the observation group. LISAplus participants were recruited in the cities of Munich ($n = 1467$, but two participants withdrew their consent to participate), Leipzig ($n = 976$), Wesel ($n = 348$) and Bad Honnef ($n = 306$) between 1997 and 1999. The GINIplus and LISAplus studies were approved by the local ethics committees and informed consent was obtained from all parents of participants. More detailed descriptions of these cohorts have been published elsewhere (Heinrich et al., 2002; von Berg et al., 2003, 2013; Zutavern et al., 2006).

The current analyses are restricted to participants residing in the city of Munich and its surrounding areas from the time of recruitment until the 10-year follow-up ($n = 1700$ from GINIplus and $n = 940$ from LISAplus), as land use data at a high resolution was only available for this study centre. The analyses were also restricted to children for whom information on behavioural problems ($n = 1478$ from GINIplus and $n = 792$ from LISAplus) and other covariates ($n = 1303$ from GINIplus and $n = 742$ from LISAplus) was available. Children who reported living at their current address (at the 10-year follow-up) for less than one year were excluded ($n = 85$ from GINIplus and $n = 28$ from LISAplus). Thus, the final study population comprised 1932 participants ($n = 1218$ from GINIplus and $n = 714$ from LISAplus).

2.2. Access to urban green spaces

The following land use types were considered as urban green spaces: "Friedhof" (cemetery), "Gartenland" (garden), "Grünanlage" (park) and "Gärtnerei" (plant nursery). The shortest distance between each child's place of residence at 10 years of age and the nearest urban green space (in metres) was used as a surrogate for urban green space access. Data for these calculations were obtained from the local Bavarian land use dataset (vector with spatial resolution of <5 m) from the Bavarian Survey Office for the year 2008. The land use data covers the entire study territory (27,521.66 km^2), which includes two administrative regions of Bavaria state: Upper Bavaria and Swabia. Data management and calculations were performed in ArcGIS 10.1 Geographical Information System (GIS) (ESRI, Redlands, CA).

2.3. Behavioural problems

Behavioural problems in children were assessed using the German version of the Strengths and Difficulties Questionnaire (SDQ) (Goodman, 1997; Woerner et al., 2004). Parents completed the SDQ on behalf of their child at the 10-year follow-up. The SDQ is an internationally disseminated and validated screening instrument used to identify behavioural problems in children and adolescents. In a recent review, the psychometric characteristics of the SDQ were reported to be strong (Stone et al., 2010). Good psychometric properties were also reported for the German version of the parent-reported SDQ in terms of reliability, based on internal consistency (Rothenberger et al., 2008; Woerner et al., 2004), and validity, based on the SDQ's ability to discriminate between clinical and community samples (Becker et al., 2004; Klasen et al., 2000).

The SDQ comprises five subscales for five items (25 items in total): emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems and prosocial behaviour. To score each item, a three-point scale ("not true", "somewhat true" and "certainly true") is used. Subscale scores and the total difficulties score were derived following the standard scoring instructions (http://www.sdqinfo.com/) and subsequently grouped into normal, borderline and abnormal categories, according to cut-off points recommended for a German population (Woerner et al., 2004). According to the standard scoring instructions, SDQ subscale scores were first prorated (mean substitution) when at most two out of five scale times were missing. Overall mental health was assessed by the total difficulties score, which was estimated by summing all subscale scores except for the prosocial behaviour score. As our study was focused on behavioural problems (i.e. difficulty subscales), the prosocial behaviour subscale (i.e. strength subscale) was not included in the analyses.

2.4. Covariates

Potential confounders were selected a priori, mainly based on our previous studies of behavioural problems in children (e.g., Tiesler et al., 2013). The following covariates were extracted from parent-completed questionnaires and considered in the current analyses: study (GINIplus observation group/GINIplus intervention group/LISAplus), sex (male/female), exact age at the 10-year follow-up (years), parental level of education (both parents with <10 years of school (low)/at least one parent with 10 years of school (medium)/at least one parent with >10 years of school (high), classified according to the German education system), age of mother at time of birth (≤30 years/>30–35 years/>35 years), single parent status at the 10-year follow-up (yes/no), time spent in front of a screen (<1 h per day in summer and ≤2 h per day in winter (low)/≥1 h per day in summer or >2 h per day in winter (high)) and time spent outdoors (≤4 h per day in summer and ≤2 h per day in winter (low)/>4 h per day in summer or >2 h per day in winter (high)).

2.5. Statistical analyses

Associations between access to urban green spaces and behavioural problems in children were assessed using proportional odds models. The proportional odds ratio (pOR) is a summary of odds ratios obtained from logistic regression models using incremental cut-points to dichotomise ordinal outcomes (Scott et al., 1997). Possible dichotomizations for the SDQ scales are (i) abnormal/borderline vs. normal and (ii) abnormal vs. borderline/normal. The assumption of homogeneity of the pOR over these two cut-points was tested with a score test. As proposed by Bender and Grouven (1998), when this assumption was violated in either crude or adjusted models, logistic regression models for the above-mentioned dichotomizations were applied and odds ratios (OR) are reported. Effects are reported per 500 m increase in the distance between a child's residence and the nearest urban green space.

All statistical analyses were performed in SAS (version 9.2; SAS Institute Inc., Cary, NC, USA).

2.6. Sensitivity analyses

As study participants were spatially spread over the inner city of Munich and its surrounding areas, we explored potential effect modification by urbanisation using an interaction term between distance to urban green spaces and whether a child lived in the inner city of Munich (yes/no) and by stratifying the main analyses by whether or not a child lived in the inner city of Munich. Since the prevalence of behavioural problems was higher among boys than girls for the total difficulties score (9.7% abnormal and 8.6% borderline in boys, 5.1% abnormal and 5.5% borderline in girls; Chi-square $p < 0.01$) and for all SDQ subscales except for emotional problems (e.g., for the hyperactivity/inattention subscale: 11.5% abnormal and 5.7% borderline in boys, 3.6% abnormal and 4.3% borderline in girls; Chi-square $p < 0.01$), we also tested for effect modification by sex using the same procedure as aforementioned.

In order to explore whether physical activity mediates the association between access to green spaces and behavioural problems, models which contained no physical activity-related covariates were compared to the main models (in which two physical activity-related covariates are included: time spent outdoors and time spent in front of screen) and to models adjusted for parent-reported child physical activity (available for 1625 children).

To test the robustness of our primary exposure variable, we conducted some further sensitivity analyses. First, access to urban green spaces was defined as the presence of urban green spaces (yes/no) in a 500-m buffer around each child's place of residence, rather than as a linear distance. A 500-m buffer, which was assumed to be a proxy for a child's neighbourhood, should represent a distance reachable within 10 min of walking (Villeneuve et al., 2012) as children have limited mobility compared to adults (Duncan et al., 2011). Previous studies examining the effects of green spaces on children and adult health have also used this buffer size (Dadvand et al., 2012; Kyttä et al., 2012; Villeneuve et al., 2012). We repeated this analysis using a 300-m buffer, which is in-line with the European Commission's recommendations for access to green spaces (Ludlow et al., 2003).

Second, to examine whether the size of an urban green space is an influential factor on the studied associations, we limited urban green spaces to those with a land area greater or equal to 5000 m^2, as has been recommended by the European Commission (Ludlow et al., 2003).

Third, we repeated the main analyses after excluding cemeteries and plant nurseries from the urban green spaces definition.

Fourth, we assessed associations using the distance between a child's residence to the nearest forest as the exposure. Forests, in contrast to artificial urban green spaces, represent natural green spaces.

Finally, we assessed associations using residential surrounding greenness, defined by the mean value of Normalized Difference Vegetation Index (NDVI) in a 500-m buffer around each child's place of residence, as the exposure. NDVI is a commonly used indicator of green vegetation. We derived NDVI from Landsat 5 Thematic Mapper (TM) satellite images from the Global Visualisation Viewer from the U.S. Geological Survey (http://earthexplorer.usgs.gov/) for the year 2003 (two images from the 14th of July and one from the 24th of August were merged to cover the study area). A detailed description of the NDVI assessment has been previously published (Markevych et al., 2014).

3. Results

The socio-demographic characteristics and exposure levels of study participants are presented in Table 1. The age of children ranged from 9.4 to 11.7 years and 51.4% of them were male. The median distance to the nearest urban green space was 289.1 m and the interquartile range was 368.1 m. The prevalence of behavioural problems among the study participants, as measured by the SDQ subscales, and the total difficulties scores are presented in Table 2. The internal consistency of the SDQ subscales and the Total Difficulties Score expressed as Cronbach's α (Cronbach, 1951) were comparable to the values obtained for the German validation sample (Woerner et al., 2004): Total Difficulties Score: 0.81; emotional symptoms: 0.68; conduct problems: 0.54; hyperactivity/inattention problems: 0.80; and peer relationship problems: 0.64.

Table 1
Characteristics of the study participants ($n = 1932$).

	Total n (%) or mean ± SD[a] or median (IQR[b])
Study	
GINIplus observation group	683 (35.4)
GINIplus intervention group	535 (27.7)
LISAplus	714 (37.0)
Sex	
Male	994 (51.4)
Female	938 (48.6)
Age (years)*	10.1 ± 0.2
Parental level of education[c]	
Low	96 (5.0)
Medium	350 (18.1)
High	1486 (76.9)
Age of mother at birth	
≤30 years	584 (30.2)
>30–35 years	921 (47.7)
>35 years	427 (22.1)
Single parent status at the 10-year follow-up	
No	1715 (88.8)
Yes	217 (11.2)
Time spent in front of a screen[d]	
Low	1451 (75.1)
High	481 (24.9)
Time spent outdoors[e]	
Low	1307 (67.7)
High	625 (32.4)
Distance to the nearest urban green space (m)**	289.1 (368.1)

[a] Standard deviation.
[b] Interquartile range.
[c] Definition based on highest parental level of education: both parents with less than 10 years of school (low), at least one parent with 10 years of school (medium), at least one parent with more than 10 years of school (high), classified according to the German education system.
[d] "Low": defined as less than 1 h per day in summer and 2 h or less per day in winter.
[e] "Low": defined as 4 h or less per day in summer and 2 h or less per day in winter.
* Mean ± SD.
** Median (IQR).

Table 2
Behavioural problems assessed by the Strengths and Difficulties Questionnaire (SDQ).

	n (%)
Total difficulties score	
Normal	1651 (85.5)
Borderline	137 (7.1)
Abnormal	144 (7.4)
Emotional symptoms	
Normal	1591 (82.4)
Borderline	130 (6.7)
Abnormal	211 (10.9)
Conduct problems	
Normal	1685 (87.2)
Borderline	162 (8.4)
Abnormal	85 (4.4)
Hyperactivity/inattention	
Normal	1687 (87.3)
Borderline	97 (5.0)
Abnormal	148 (7.7)
Peer relationship problems	
Normal	1771 (91.7)
Borderline	86 (4.5)
Abnormal	75 (3.9)

Table 3
Associations between the distance to the nearest urban green space and behavioural problems assessed by the Strengths and Difficulties Questionnaire (SDQ). Results are presented as proportional odds ratios (pOR) or odds ratios (OR) with corresponding 95% confidence intervals (CI).

	Crude pOR or OR[a] (95% CI)[b]	Adjusted[c] pOR or OR (95% CI)
Total difficulties score	1.05 (0.91–1.21)	1.07 (0.92–1.23)
Emotional symptoms	0.96 (0.83–1.11)	0.96 (0.83–1.11)
Conduct problems	1.04 (0.89–1.21)	1.03 (0.89–1.20)
Hyperactivity/inattention		
Abnormal/borderline vs. normal	1.11 (0.97–1.28)	1.13 (0.98–1.30)
Abnormal vs. borderline/normal	**1.18 (1.00–1.39)**	**1.20 (1.01–1.42)**
Peer relationship problems	**1.18 (1.01–1.38)**	**1.20 (1.02–1.40)**

Bold text indicates statistical significance at the 5% level.
[a] Proportional odds ratios are homogenous across the cutoffs of the ordinal SDQ variables. If the crude or adjusted models violated this assumption, cutpoint-specific odds ratios are reported.
[b] Effects reported per 500 m increase in the distance to the nearest urban green space.
[c] Adjusted for study, sex, age, parental level of education, age of mother at time of birth, single parent status at the 10-year follow-up, time spent in front of a screen and time spent outdoors.

Associations between access to urban green spaces and behavioural problems are reported in Table 3. A larger distance to the nearest urban green space was statistically significantly associated with an increased risk of hyperactivity and inattention problems, especially among children with abnormal SDQ values compared to children with borderline or normal values (OR = 1.20 (95% confidence interval (CI) = 1.01–1.42)). There was also an association with peer relationship problems (pOR = 1.20 (95% CI = 1.02–1.40)). For overall behavioural problems and for conduct problems, associations were similar in trend but not statistically significant. Finally, a larger distance to an urban green space was positively but not statistically significantly associated with less emotional symptoms.

The interaction term between urban green spaces and urbanisation was not significant. In the stratified analyses, associations between urban green spaces and behavioural problems were slightly stronger for children living in the inner city of Munich (n = 782) compared to those living in the surrounding suburban areas (n = 1150) (Supplementary Fig. 1).

Associations between urban green spaces with overall mental health and hyperactivity/inattention problems were modified by sex (p-value of interaction terms <0.05). Among males, a larger distance to the nearest urban green space was associated with an increased risk of mental health problems and hyperactivity/inattention problems (analyses stratified by sex presented in Supplementary Table 1). All associations among females were null.

The main findings were robust to the inclusion/exclusion of all physical activity-related variables investigated (data not shown).

Fig. 1 summarises the results of the sensitivity analysis in which behavioural problems are compared between children living closer (n = 503) or further than 500 m (n = 1429) away from the nearest urban green space. We observed a statistically significant association for hyperactivity/inattention (OR = 1.49 (95% CI = 1.10–1.99) for children with abnormal or borderline values compared to those with normal values; OR = 1.79 (95% CI = 1.24–2.57) for children with abnormal values compared to children with borderline or normal values). There was also a statistically significant association between the absence of urban green spaces in a 500-m buffer around a child's place of residence and greater overall mental health problems (pOR = 1.41 (95% CI = 1.06–1.87)). When we repeated these analyses using a 300-m buffer (937 children reside within 300 m of an urban green space), the association with hyperactivity/inattention problems was similar but weaker (OR = 1.21 (95% CI = 0.92–1.60) for children with abnormal or borderline values compared to children with normal values; OR = 1.45 (95% CI = 1.02–2.04) for children with abnormal values compared to those with borderline or normal values). All other associations were not significant.

The association between access to green spaces and hyperactivity/inattention problems was no longer significant after excluding urban green spaces smaller than 5000 m^2 (OR = 0.95 (95% CI = 0.75–1.19) for children with abnormal or borderline values compared to children with normal values; OR = 1.06 (95% CI = 0.82–1.38) for children with abnormal values compared to children with borderline or normal values). The association between access to green spaces and peer

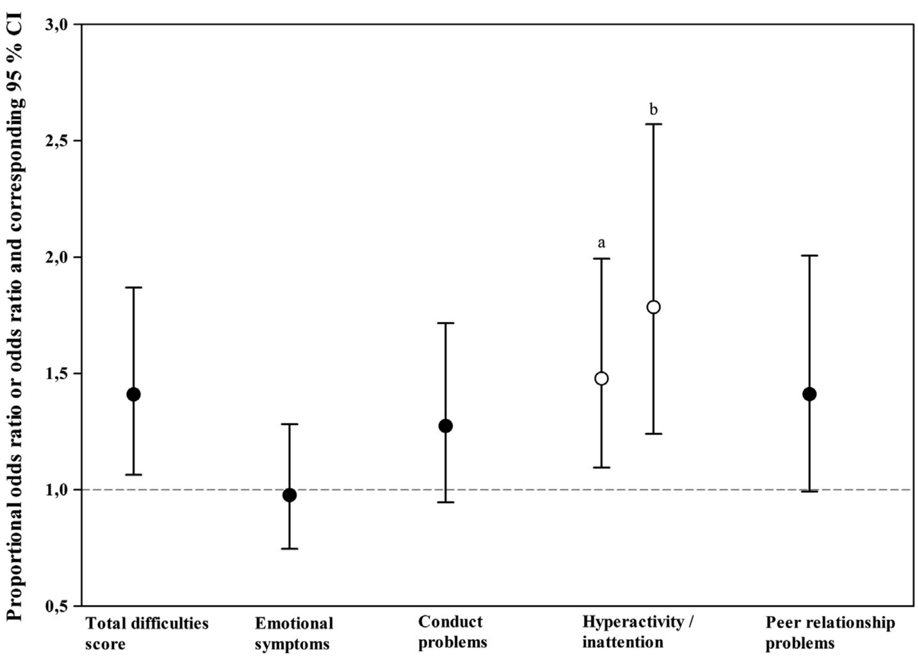

Fig. 1. Associations between urban green spaces within a 500-m buffer around the residential address and behavioural problems assessed by the Strengths and Difficulties Questionnaire (SDQ). All models are adjusted for study, sex, age, parental level of education, age of mother at time of birth, single parent status at the 10-year follow-up, time spent in front of a screen and time spent outdoors. Black circles indicate proportional odds ratios; white circles indicate odds ratios (a — abnormal/borderline vs. normal, b — abnormal vs. borderline/normal).

relationship problems was also attenuated and no longer statistically significant (pOR = 1.11 (95% CI = 0.87–1.42)).

When cemeteries and plant nurseries were excluded from the urban green space definition, a larger distance to urban green spaces remained significantly associated with an increased OR for hyperactivity and inattention problems (1.06 (95% CI = 1.01–1.13) for children with abnormal or borderline values compared to children with normal values; 1.07 (95% CI = 1.00–1.15) for children with abnormal values compared to children with borderline or normal values).

Poorer access to forests and residential surrounding greenness, as measured by NDVI, were not associated with behavioural problems in children (data not shown).

4. Discussion

4.1. Key findings

Hyperactivity/inattention and peer relationship problems in 10-year old children were positively associated with increasing distances to urban green spaces. The effects were slightly stronger for children residing in the inner city of Munich. When stratified by sex, the observed association with hyperactivity/inattention was only statistically significant among males. Children living further than 500 m away from any urban green space had more overall behavioural problems than those living within 500 m of an urban green space. When small (<5000 m^2) green spaces were excluded from the analysis, no statistically significant associations were observed. Finally, behavioural problems were not associated with the distance to a forest or with residential surrounding greenness.

4.2. Interpretation of the results

Hyperactivity and inattention are symptoms of attention-deficit/hyperactivity disorder (ADHD), which is among the most commonly diagnosed child psychiatric disorder. More than 5% of children are affected worldwide (Polanczyk et al., 2007). ADHD is characterised by elevated impulsivity, increased motor activity, impaired concentration and short-term memory deficits, all of which can reduce school performance (Schmiedeler and Schneider, 2013). The observed association with hyperactivity/inattention problems was quite robust in our study, and remained significant in two of the sensitivity analyses (exclusion of cemeteries and plant nurseries from the urban green space definition and dichotomization of the exposure as yes/no urban green space in a child's neighbourhood). However, in these same two sensitivity analyses, associations with peer relationship problems were attenuated. Whether a true independent causal link exists for each outcome requires further examination, especially for peer relationship problems, which were less consistently associated with urban green spaces in our study.

There are several theories which attempt to explain the psychological benefits of green spaces. Among them, is a purported effect of physical activity (Fan et al., 2011; Lee and Maheswaran, 2010). Better access to green spaces is hypothesised to increase the frequency and level of physical activity by decreasing the perception of effort and increasing levels of motivation (Gladwell et al., 2013). Moreover, physical activity conducted outdoors in green environments has been shown to lead to greater feelings of revitalization and positive engagement compared to physical activity conducted indoors (Gladwell et al., 2013). Interestingly, although many studies have recently investigated the link between objectively measured neighbourhood green spaces and physical activity in adolescents and children (Ding et al., 2011; Lee and Maheswaran, 2010), the results remain inconsistent. Unfortunately, we did not have data on objectively measured physical activity or information on whether physical activity was being conducted in urban green spaces. Nevertheless, the results of the two sensitivity analyses we conducted to examine any effect mediation by questionnaire-derived physical activity yielded null findings.

A second hypothesis is that any green space-related benefits may be explained by the restorative and stress-mitigating effects of green spaces, as summarised by the complementing stress reduction theory (SRT) (Ulrich et al., 1991) and attention restoration theory (ART) (Kaplan, 1995). The SRT describes how exposure to nature may activate affective response, behavioural approach orientation and continuously relaxed attention (Ulrich et al., 1991). The ART, on the other hand, emphasises that the natural environment may alleviate recovery from mental fatigue caused by directed attention (Kaplan, 1995). In line with these theories, it has been reported that walking or playing in green environments reduces symptoms of ADHD in children (Kuo and Taylor, 2004; Lee and Maheswaran, 2010; Searight et al., 2012; Taylor and Kuo, 2009; van den Berg and van den Berg, 2010). Both the SRT and ART suggest that contact with any type of green space (even just a physical presence in them) and greenness itself may be beneficial for mental health. However, our results indicate that for our study population of 10-year old children, urban green spaces were most important. All associations with natural green spaces (forests) were null. Unfortunately, we did not have information on the time spent in specific green spaces and activities conducted there. We might suppose that urban green spaces are most attractive for 10-year old children, as they are likely better maintained and may be perceived to be safer than forests. Moreover, due to perceived lack of safety and insufficient maintenance, 10 year-old children might not be allowed to wander alone in forests. The null findings for surrounding greenness may indicate that access to structured urban green spaces is more important for children than having a high level of green vegetation in the neighbourhood.

In line with our primary assumption, we found that effect estimates were slightly stronger in the inner city of Munich compared to its surroundings. We hypothesise that there is a general lack of green spaces in urban areas, and thus parks and gardens play a more important role for urban residents than for those living in suburban or rural areas, in which natural green spaces are more prevalent.

In stratified analyses, the associations with overall mental health and hyperactivity/inattention were significant only among males. It is possible that there may be sex differences in the usage (frequency and type of activity) of urban green spaces. It is also possible that boys may be more likely to be allowed to use neighbourhood green spaces unsupervised than girls. However, we did not have the necessary data to verify either of these assumptions. Nevertheless, this finding suggests that poor access to urban green spaces might affect the psychological health of 10-year-old boys to a greater extent than girls of the same age. This observation may be important when considering that ADHD is more prevalent in males than females (Polanczyk et al., 2007).

The attenuation of the associations after excluding small green spaces from the exposure definition may suggest that small urban green spaces play an important role among children.

The association between an absence of neighbourhood green spaces and worse overall mental health among children, and especially boys, is consistent with previous studies conducted mainly among adults. A recent literature review, which included 35 articles (Lee and Maheswaran, 2010), reported that green spaces may benefit the well-being and mental health of children and adults. A second systematic review, which included 25 studies and focused mainly on the short-term effects of green spaces in different age groups (Bowler et al., 2010), suggested that green environments may have positive effects on well-being and emotional health. In a cross-sectional study conducted in Turku, Finland, which included 1837 children and adolescents, a larger proportion of green spaces in a 500-m buffer around the place of residence was associated with better perceived health. In a large survey conducted in New Zealand (n = 8157), adolescents and adults who lived in neighbourhoods with more green spaces had better mental health than those with less green spaces (Richardson et al., 2013). In a study including 9230 Swedish adults, the risk of having self-reported poor mental health was lower among those with green spaces within a 300-m buffer around the place of residence and among physically active women (Annerstedt et al., 2012). In a cross-sectional study conducted in Chicago on 1544 adults, green spaces were found to mitigate stress (Fan et al., 2011).

4.3. Limitations

The cross-sectional design of our study is its main limitation. Causal relationships cannot be inferred, and it is not possible to determine whether the observed effects may be due to a lagged association between green spaces and mental health. We are also unable to exclude the effect of any self-selection bias on the associations. That is, that parents from a higher SES are more likely to select living in greener neighbourhoods and to have less behavioural problems. Our results are also prone to attrition bias as GINIplus participants (especially those from the observation group), and those born to young mothers were less likely to be included in the current analyses. Furthermore, families with a lower level of education and income were less likely to be initially recruited and to continue participating in the 10-year follow-up of the GINIplus and LISAplus cohorts. Therefore, as in the case with the Danish National Birth Cohort, children with a lower socioeconomic status are under-represented in this analysis, and the generalizability of our findings is questionable (Jacobsen et al., 2010). Moreover, we did not have data on area-level SES, which could be a source of residual confounding. Neighbourhood SES could be associated with both behavioural problems and access to green spaces, with more deprived neighbourhoods being less green and having a higher prevalence of behavioural problems in children (Kalff et al., 2001). Nevertheless, we cautiously adjusted our models for variables representing socioeconomic status, such as parental education level and single parent status at the 10-year follow-up. Since only 5% of the study participants had parents with a low parental education level, it was not possible to carry out analyses stratified by parental education level. A further limitation is that we were unable to control for parental psychopathology, physical health and activity, as well as parenting methods which may be sources of residual confounding. Moreover, there is a potential for exposure misclassification as we used the linear distance from a child's residence to the nearest urban green space as a surrogate for access to urban green spaces. Unfortunately, we did not have information on which green spaces (the nearest, the second nearest, etc.) each child visits, and how often. However, we conducted an additional analysis using presence or absence of urban green spaces in the neighbourhood as a dichotomous exposure variable, and our main findings remained robust. We also did not have information on quality characteristics of green spaces, such as their accessibility to the public, perceived safety, availability of playgrounds, maintenance, and occurrence of organised events, all of which could result in residual confounding. Moreover, we were unable to control for indoor greenness (i.e. houseplants) and for own (not public) green spaces (i.e. backyards/gardens). Finally, behavioural problems in children were assessed by a screening questionnaire and unfortunately, could not be confirmed by a physician's diagnosis.

5. Conclusions

Our findings suggest that children with poorer access to urban green spaces are more likely to have hyperactivity/inattention problems at 10 years of age. This association was only significant in males. Moreover, the absence of urban green spaces in a child's neighbourhood was associated with poorer overall mental health. Behavioural problems were not associated with the distance to a forest or with residential surrounding greenness. Given the general lack of studies on the influence of green spaces on mental health of children, further research is warranted and our observed associations should be replicated.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2014.06.002.

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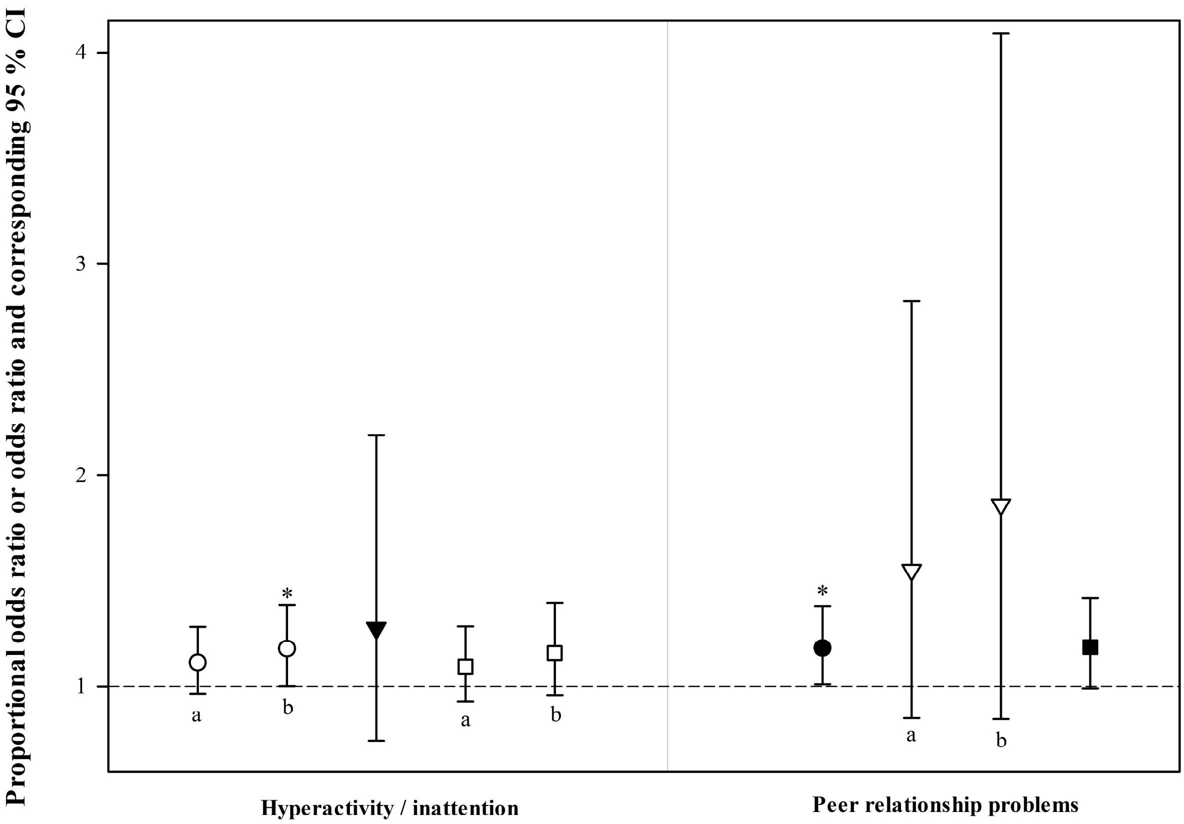
Paper 2: Supplementary Material



Supplementary figure 1. Associations between the distance to the nearest urban green space and behavioural problems assessed by the Strengths and Difficulties Questionnaire (SDQ), stratified by whether the residence is in the inner city of Munich or the surrounding suburban areas. Results are presented per 500 m increase in distance to the nearest urban green space. All models are adjusted for study, sex, age, parental level of education, age of mother at time of birth, single parent status at the 10-year follow-up, time spent in front of a screen and time spent outdoors. Inverse triangles indicate the inner city of Munich; squares indicate the surrounding areas; circles indicate results for the total population. Black color indicates proportional odds ratios; white indicates odds ratios (a - abnormal / borderline *vs.* normal, b - abnormal *vs.* borderline / normal). Asterixes indicate statistical significance at the 5 % level.

Supplementary table 1

Associations between the distance to the nearest urban green space and behavioural problems assessed by the Strengths and Difficulties Questionnaire (SDQ), stratified by sex. Results are presented as proportional odds ratios (pOR) or odds ratios (OR) with corresponding 95 % confidence intervals (CI).

	Adjusted[a] pOR or OR[b] (95 % CI)[c]	
	Males (*n* = 994)	Females (*n* = 938)
Total difficulties score	**1.21 (1.02 – 1.44)**	0.79 (0.58 – 1.07)
Emotional symptoms	1.06 (0.87 – 1.27)	
Abnormal / borderline *vs.* normal		0.84 (0.66 – 1.07)
Abnormal *vs.* borderline / normal		0.88 (0.66 – 1.19)
Conduct problems	1.01 (0.84 – 1.23)	1.05 (0.82 - 1.35)
Hyperactivity / inattention	**1.28 (1.08 – 1.50)**	0.75 (0.52 – 1.09)
Peer relationship problems	1.20 (0.98 -1.47)	1.17 (0.89 – 1.54)

[a]Adjusted for study, age, parental level of education, age of mother at time of birth, single parent status at the 10-year follow-up, time spent in front of a screen and time spent outdoors. Bold text indicates statistical significance at the 5 % level.

[b]Proportional odds ratios are homogenous across the cutoffs of the ordinal SDQ variables. If the crude or adjusted models violated this assumption, cutpoint-specific odds ratios are reported.

[c]Effects reported per 500 m increase in the distance to the nearest urban green space.

7 Paper 3: Greenness and Blood Pressure in Children

(Markevych et al. BMC Public Health, 2014)

Original title:	A cross-sectional analysis of the effects of residential greenness on blood pressure in 10-year old children: Results from the GINIplus and LISAplus studies
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RESEARCH ARTICLE Open Access

A cross-sectional analysis of the effects of residential greenness on blood pressure in 10-year old children: results from the GINIplus and LISAplus studies

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Abstract

Background: According to Ulrich's psychoevolutionary theory, contact with green environments mitigates stress by activating the parasympathetic system, (specifically, by decreasing blood pressure (BP)). Experimental studies have confirmed this biological effect. However, greenness effects on BP have not yet been explored using an observational study design. We assessed whether surrounding residential greenness is associated with BP in 10 year-old German children.

Methods: Systolic and diastolic BPs were assessed in 10 year-old children residing in the Munich and Wesel study areas of the German GINIplus and LISAplus birth cohorts. Complete exposure, outcome and covariate data were available for 2,078 children. Residential surrounding greenness was defined as the mean of Normalized Difference Vegetation Index (NDVI) values, derived from Landsat 5 TM satellite images, in circular 500-m buffers around current home addresses of participants. Generalized additive models assessed pooled and area-specific associations between BP and residential greenness categorized into area-specific tertiles.

Results: In the pooled adjusted model, the systolic BP of children living at residences with low and moderate greenness was 0.90 ± 0.50 mmHg (p-value = 0.073) and 1.23 ± 0.50 mmHg (p-value = 0.014) higher, respectively, than the systolic BP of children living in areas of high greenness. Similarly, the diastolic BP of children living in areas with low and moderate greenness was 0.80 ± 0.38 mmHg (p-value = 0.033) and 0.96 ± 0.38 mmHg (p-value = 0.011) higher, respectively, than children living in areas with high greenness. These associations were not influenced by environmental stressors (temperature, air pollution, noise annoyance, altitude and urbanisation level). When stratified by study area, associations were significant among children residing in the urbanised Munich area but null for those in the rural Wesel area.

Conclusions: Lower residential greenness was positively associated with higher BP in 10 year-old children living in an urbanised area. Further studies varying in participants' age, geographical area and urbanisation level are required.

Keywords: Greenness, NDVI, Blood pressure, Children, Green spaces

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Background

Over half of the world's population lives in urban areas [1] and are thus often exposed to higher levels of environmental stressors (i.e. crowding, air and heat pollution, noise) than individuals living in rural areas. Contact with nature is believed to mitigate stress, as has been demonstrated in recent epidemiological studies [2-5]. Good access to structured green spaces as well as a high overall level of vegetation at residences (i.e. greenness) have been shown to alleviate stress [2-5].

The mechanisms by which green environments lead to stress restoration have been described, in particular, by Ulrich's psychoevolutionary theory [6]. This theory argues that because human species have evolved over a long period in natural environments, they are physiologically and possibly psychologically better adapted to natural settings than artificial urban settings. Exposure to nature, according to Ulrich, induces an affective response by numerous physiological systems that leads to a reduction of sympathetic outflow measures, such as heart rate, cortisol level and blood pressure (BP) [6].

In line with Ulrich's theory, exposure to nature scenes in laboratory settings and walking in green environments have been shown to lower BP, although marginally, in several experimental studies conducted in adults [7-12]. However, to date, no single study has investigated the effects of green spaces or greenness on BP using an observational study design. We aimed to fill this research gap by exploring whether greenness around the current home residence is associated with BP in 10 year-old German children. We believe children may be a particularly useful study population as they do not often take medications that can influence their BP, unlike adults.

Methods

Study population

The current analyses are based on data from two ongoing German birth cohorts: the "German Infant Study on the Influence of Nutrition Intervention plus Environmental and Genetic Influences on Allergy Development" (GINIplus) and the "Influence of Life-Style Factors on the Development of the Immune System and Allergies in East and West Germany plus the Influence of Traffic Emissions and Genetics" (LISAplus). Both cohorts have similar study designs and recruited only healthy full-term neonates with a normal birth weight. GINIplus participants were recruited in the cities of Munich and Wesel between 1995 and 1998 (N = 5,991). This cohort consists of two study groups: an observational study group and a study group that participated in an intervention trial with hypoallergenic formulae [13,14]. LISAplus participants were recruited in the cities of Munich, Leipzig, Wesel and Bad Honnef between 1997 and 1999 (N = 3,097) [15,16]. The GINIplus and LISAplus studies have been approved by their local ethics committees (Bavarian General Medical Council, University of Leipzig, Medical Council of North-Rhine-Westphalia) and informed consent was obtained from all parents of participants.

The current analyses are restricted to participants who resided in the Munich and Wesel study areas both at birth and at the 10 year follow-up. Furthermore, home address, BP and covariate data were required for inclusion. The final study population is comprised of 2,078 participants (N = 1,256 (52.1% male) from the Munich study area and N = 822 (50.7% male) from the Wesel study area).

Greenness

Greenness was assessed using the Normalized Difference Vegetation Index (NDVI), derived from Landsat 5 Thematic Mapper (TM) satellite images (http://earthexplorer.usgs.gov/). NDVI is a common indicator of green vegetation which was developed to analyse surface reflectance measurements. The NDVI is based on two vegetation-informative bands (near-infrared (NIR) and visible red (RED)) and is calculated using the formula: NDVI = (NIR − RED)/(NIR + RED). NDVI values range from −1 to +1, with +1 indicating a high density of green leaves, −1 representing water features and values close to zero referring to barren areas of rock, sand or snow [17].

For both the Munich and Wesel study areas, we chose cloud-free images taken during summer months in 2003 for the NDVI calculation. For the Munich area, which includes two administrative regions of Bavaria (Upper Bavaria and Swabia; Figure 1), we used three images (two from the 14th of July and one from the 24th of August) as data covering the entire study area were not available for a single day. These three images were merged to obtain complete coverage of the Munich study area. For the Wesel study area, which includes two administrative regions of North-Rhein Westphalia (Münster and Düsseldorf; Figure 1), we used one image from the 10th of July. Based on these images, NDVI values were calculated at a resolution of 30 m by 30 m. Negative values of NDVI were excluded before further calculation. Residential surrounding greenness was defined as the mean of NDVI values in a circular 500 m buffer around each participant's home address. A 500 m buffer should represent a distance reachable within 10 minutes of walking [18] and is assumed to be a proxy for a child's neighbourhood, as children are not as mobile as adults [19]. Previous studies on greenness and child and adult health, some of which were conducted by our group, have used this same buffer size [18,20-22].

Data management and calculations of NDVI were conducted using the ArcGIS 10.0 Geographical Information System (GIS) (ESRI, Redlands, CA) and Geospatial Modelling Environment (GME) (Spatial Ecology LLC) softwares.

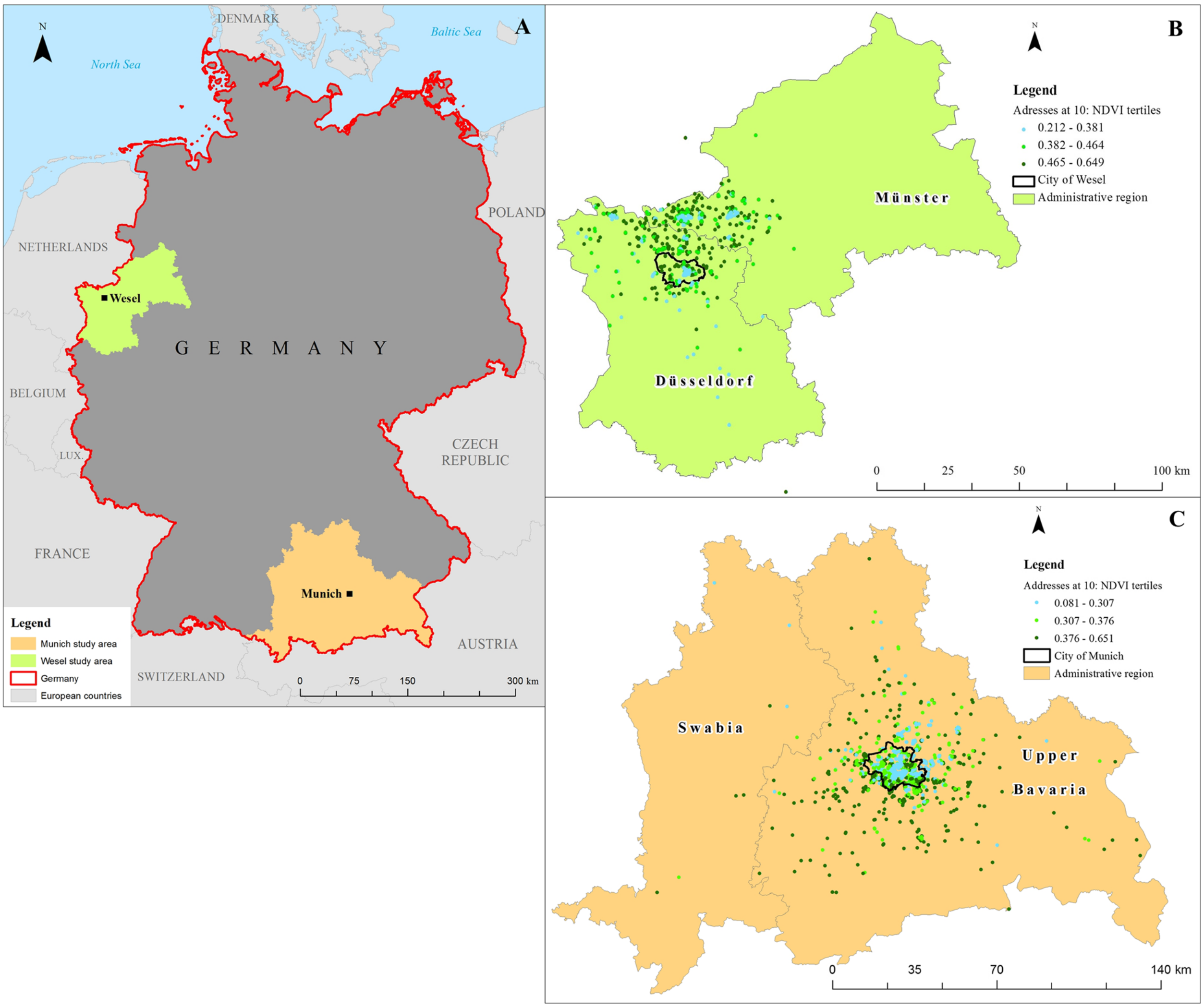

Figure 1 **Location of the Munich and Wesel study areas on the map of Germany (A) and spatial distribution of the NDVI tertiles among participants residing in the Wesel (B) and Munich (C) study areas.**

Blood pressure

Systolic and diastolic arterial BPs in children were measured during a physical examination at the 10-year follow up of the cohorts (2005 to 2009). The standardized protocol followed was the same as used in the population-based German Health Interview and Examination Survey for Children and Adolescents (KiGGS 2003–2006) [23]. Briefly, the first BP measurement was taken on the right arm when the child was in a sitting position and had rested for five minutes. A second measurement was taken after sitting for a further two minutes. The cuff size was selected according to the length and circumference of the upper arm of each child; the width was at least 2/3 the length and the pressure bladder covered at least half of the circumference of the upper arm. For the current analyses, an average of the two valid BP measurements was used, regardless of their difference. All measurements were performed by one physician in Munich and a second one in Wesel between 7:00 a.m. and 8:30 p.m. using an automatic BP monitor (Omron M5 Professional). A more detailed methodological description of the BP measurements for the two cohorts has been previously published [24,25].

Covariates

Data on the following covariates were extracted from parent-completed questionnaires: study (GINIplus observational group/GINIplus interventional group/LISAplus), sex (male/female), parental education (both parents with < 10 years of school (low)/at least one parent with 10 years of school (medium)/at least one parent with > 10 years of school (high), according to the German education system) and parental hypertension (neither of the parents had hypertension, one of the parents had hypertension). The exact child's age (in years) and the season (winter/spring/summer/autumn) at the time of the BP measurements were also available. The height and weight of each child at 10 years were also obtained when the BP measurements were conducted and used to calculate body mass index (BMI, kg/m^2).

Statistical analyses

Associations between residential surrounding greenness, estimated by NDVI, with systolic and diastolic BP were assessed using generalized additive models (GAMs; R package mgcv). GAMs allow the estimation of non-linear relationships between continuous predictor variables and a dependent variable via smooth functions [26]. Relationships between NDVI and BP were not linear and the pattern differed across the two study areas (Additional file 1: Figure S1). Therefore, we categorized NDVI values into tertiles in order to obtain numerical effect estimates and capture the pattern of the relationship, while maintaining a sufficient number of observations in each category, as has been previously done [27]. Associations between all continuous covariates and outcome variables were tested for linearity by incorporating the covariates as smooth terms. In the case of a non-linear relationship between a covariate and an outcome variable, the covariate was analyzed as a smooth term. Associations were investigated in the pooled study population using area-specific NDVI tertiles and adjustments for study centre and all covariates described in the above section. Area-specific models were also examined and adjusted for the same covariates, but study centre was excluded. All analyses were conducted using the statistical software R, version 3.0.2 [28].

Further analyses: impact of environmental stressors

To explore whether associations between surrounding residential greenness and BP are influenced and/or mediated by environmental stressors, we conducted the following additional analyses.

Temperature

Outdoor temperature is known to influence both BP [29] and vegetation. Due to the high correlation between season and temperature, we were unable to include both covariates into a single model. Therefore, we excluded season from the models and instead adjusted for mean daily temperature on the day of each measurement.

Altitude

Ten year-old children residing at a high altitude have been reported to have higher BPs compared to those living at a low altitude [30]. As the terrain of the two current study areas differs significantly (the Wesel area is flat while the altitudes of the Munich residences vary from 369 m to 945 m), we additionally adjusted our models for altitude of residence but excluded study centre from pooled models to avoid collinearity. Altitude values were calculated at a 90 m spatial resolution using the Shuttle Radar Topography Mission (SRTM) dataset (http://dds.cr.usgs.gov/srtm/version1/Eurasia/).

Level of urbanisation

To test whether the effect of residential greenness on BP reflects a possible urbanisation effect, we adjusted our models for centre-specific population density tertiles derived in 5,000 m buffers around the residences, as has been done in a previous study by our group [31]. Data for these calculations were obtained from the WiGeoGIS population density dataset at a spatial resolution of 125 m for the year 2008.

Air pollution

In a previous analysis by our group, air pollution was not found to be associated with BP [32]. Nevertheless, we explored the potential role of air pollution on the association between greenness and BP by additionally adjusting the models for individual-level estimates of particulate matter (PM; including $PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2) modelled to the home address of each child at 10 years of age. These air pollution estimates were derived using land use regression models developed separately for the Munich and Wesel areas as part of the European Study of Cohorts for Air Pollution Effects (http://www.escapeproject.eu/) [33-36].

Road traffic noise annoyance

In an experimental study, vegetation was reported to attenuate perceived traffic noise by affecting an individual's emotional processing [37]. Therefore, we adjusted the models for road traffic noise annoyance, as reported by the parents of participants in the 10 year follow-up questionnaire. The original eleven category scale (from 0 to 10) was recoded into three levels of road traffic noise annoyance: low (0 and 1, no annoyance at all), medium (categories 2 to 5) and high (6 to 10, strong to unbearable annoyance) [38].

Sensitivity analyses

Since BP is known to have circadian variation, we additionally adjusted the models for time of BP measurement (7:00 to 11:00/11:01 to 14:00/14:00 to 20:30) for the participants for whom this information was available (N = 1,091 (52.7 %)). Furthermore, we excluded participants who were living at their current address for less than one year (remaining N = 1,988, as 90 participants had moved within the previous 12 months). Additionally, we conducted stratified analyses between non-movers vs. movers between 6 and 10 years and between birth and 10 years. Moreover, in order to explore whether physical activity influences the association between greenness and BP, we additionally adjusted the models for parent-reported child physical activity. Finally, to assess the stability of the NDVI estimates, we chose alternative cloud-free days in 2006 to calculate a second set of NDVI values which were used to replicate all analyses (two images from 20^{th} of June and one from the 13^{th} for the Munich area and one image from the 18^{th} of July for the Wesel area; N = 2,036, because 42 addresses in the Munich area were covered by clouds).

Results

Study participant characteristics and their exposure levels are provided for the pooled population and by study area in Table 1. The average systolic and diastolic BP in the pooled population was 111.3 ± 10.0 mmHg and 64.2 ± 7.5 mmHg, respectively. Children residing in the Wesel study area had a statistically significantly higher mean systolic BP compared to those living in the Munich area (113.2 ± 10.2 mmHg and 110.0 ± 9.6 mmHg, respectively). The same was true for diastolic BP (66.0 ± 7.0 mmHg and 62.9 ± 7.5 mmHg, respectively). The Wesel study participants differed from the Munich participants in numerous characteristics: they were slightly older, had higher BMI, and there were more participants from low SES families, all of which may result in higher BPs in Wesel. Average residential greenness, as measured by NDVI, was significantly higher in the more rural Wesel area than in the urbanised Munich area (0.430 ± 0.083 and 0.347 ± 0.089, respectively).

Associations between residential greenness with systolic and diastolic BP are presented in Table 2. Crude and adjusted associations were similar. In the adjusted model, children residing in places with low levels of greenness had systolic BPs that were on average 0.90 ± 0.50 mmHg higher (p-value = 0.073) than the BPs of children living in areas with high levels of greenness, although this result was not statistically significant. Children with moderate levels of greenness had systolic BPs that were on average 1.23 ± 0.50 mmHg higher (p-value = 0.014) than the BPs of children living in areas with high levels of greenness. In this adjusted model, study centre, BMI, season of BP measurement and parental hypertension were significant terms. Similarly, children with low and moderate levels of greenness had diastolic BPs that were on average 0.80 ± 0.38 mmHg (p-value = 0.033) 0.96 ± 0.38 mmHg (p-value = 0.011) higher than the BPs of children living in areas with high levels of greenness. In this adjusted model, study centre, BMI, sex and parental hypertension were significant terms. Effect estimates remained robust when models were individually adjusted for environmental stressors (Table 2).

Study-specific associations between greenness with systolic and diastolic BP are presented in Table 3. In the adjusted model for the Munich area, children with low and medium levels of greenness had systolic BPs that were on average 1.02 ± 0.63 mmHg (p-value = 0.106) and 2.22 ± 0.63 mmHg (p-value < 0.001) higher, respectively, than the BPs of children living in areas with high levels of greenness. Similarly, children with low and medium levels of greenness had diastolic BPs that were on average 1.08 ± 0.50 mmHg (p-value = 0.030) and 1.46 ± 0.50 mmHg (p-value 0.004) higher, respectively, than the BPs of children living in areas with high levels of greenness. All estimates for the Wesel area were not significantly different from null.

Accounting for the time of BP measurements and excluding children who had lived at their home address for less than one year did not change the estimates (data not shown). Associations stratified by moving behaviour did not yield any consistent patterns (data not shown). The estimates were robust to the inclusion of physical activity (data not shown) to the models. Furthermore, pooled and study-specific associations were similar when alternative cloud-free days for the year 2006 were used to assess NDVI values (data not shown).

Discussion

Lower levels of residential greenness were positively associated with higher systolic and diastolic BPs in 10 year-old German children. The observed associations were robust to model adjustments for environmental stressors, such as ambient temperature and air pollution, noise annoyance, altitude and level of urbanisation. However, when stratified by study area, the associations were only significant in the urban Munich study area. Risk estimates were not significantly different from null in the rural Wesel study area.

We are the first to investigate associations between objectively assessed residential greenness and BP in children using an observational study design. The few previous studies on this topic have used experimental study designs and are limited to adults [7-12]. These studies, conducted in both laboratory and natural settings, have aimed to assess physiological stress reductions induced by walking in green spaces or simply seeing greenness. Ulrich et al. conducted the first such study in 120 undergraduate volunteers at the University of Delaware, USA [12]. In this study, the systolic BP of subjects who watched a videotape of natural environments after being exposed to a stressor decreased faster and more consistently than the systolic BP of participants who watched a videotape of urban environments. This finding was replicated in 160 college-age participants from the USA [11]. Hartig et al. [10] conducted a study among 112 young students from the University of California, USA and found that after conducting tasks, sitting in a room with views of trees induced a more rapid reduction in diastolic BP compared to sitting in a room with no view. Moreover, walking in a

Table 1 Characteristics of the study participants

	N (%) or Mean ± SD[a] or Median (IQR[b])		
	Pooled (N = 2,078)	**Munich (N = 1,256)**	**Wesel (N = 822)**
Systolic blood pressure (mmHg)[§]*	111.3 ± 10.0	110.0 ± 9.6	113.2 ± 10.2
Diastolic blood pressure (mmHg)[§]*	64.2 ± 7.5	62.9 ± 7.5	66.0 ± 7.0
Study*			
GINIplus observational group	773 (37.2)	370 (29.5)	403 (49.0)
GINIplus interventional group	754 (36.3)	448 (35.6)	306 (37.2)
LISAplus	551 (26.5)	438 (34.9)	113 (13.8)
Sex			
Male	1,071 (51.5)	654 (52.1)	417 (50.7)
Female	1,007 (48.5)	602 (47.9)	405 (49.3)
Age (years)[§]*	10.2 ± 0.2	10.2 ± 0.2	10.3 ± 0.2
BMI (kg/m^2)[§]*	17.4 ± 2.5	17.0 ± 2.3	18.0 ± 2.7
Season of blood pressure measurements			
Winter	418 (20.1)	272 (21.7)	146 (17.7)
Spring	495 (23.8)	302 (24.0)	193 (23.5)
Summer	615 (29.6)	356 (28.3)	259 (31.5)
Autumn	550 (26.5)	326 (26.0)	224 (27.3)
Parental education[c]*			
Low	135 (6.5)	55 (4.4)	80 (9.7)
Medium	538 (25.9)	224 (17.8)	314 (38.2)
High	1,405 (67.6)	977 (77.8)	428 (52.1)
Parental hypertension[d]			
Yes	316 (15.2)	202 (16.1)	114 (13.9)
No	1,762 (84.8)	1,054 (83.9)	708 (86.1)
Residential surrounding greenness (NDVI[e])[§]* in a 500 m buffer around the residence			
Low	-	0.255 ± 0.045	0.340 ± 0.035
Moderate	-	0.341 ± 0.020	0.425 ± 0.024
High	-	0.445 ± 0.057	0.524 ± 0.041
Mean daily temperature on the day of blood pressure measurements (°C)[¶]*	12.0 (10.4)	10.9 (11.3)	13.0 (9.1)
Altitude of residence (m)[¶]*	498.0 (509.0)	532.0 (44.0)	26 (17)
Population density around residence (people/km^2)[§f]*			
Low	-	304.2 ± 152.0	176.2 ± 47.8
Moderate	-	1,558.6 ± 702.5	352.0 ± 93.1
High	-	5,479.8 ± 1,747.7	883.8 ± 292.7

Table 1 Characteristics of the study participants *(Continued)*

$PM_{2.5}$ concentration at residence (μg/m^3)[§]*	14.9 ± 2.2	13.3 ± 0.9	17.4 ± 0.7
PM_{10} concentration at residence (μg/m^3)[§]*	22.2 ± 3.3	20.0 ± 2.3	25.4 ± 1.3
NO_2 concentration at residence (μg/m^3)[§]*	21.3 ± 4.8	19.8 ± 5.1	23.6 ± 3.0
Road traffic noise annoyance[g]			
Low	1,367 (65.8)	821 (65.4)	546 (66.4)
Medium	608 (29.2)	371 (29.5)	237 (28.8)
High	103 (5.0)	64 (5.1)	39 (4.8)

[a]. SD: Standard deviation.
[b]. IQR: Interquartile range.
[c]. Low: < 10 years of school; Medium: 10 years of school; High > 10 years of school, according to the German education system.
[d]. No: neither of the parents had hypertension; Yes: one or both parents had hypertension.
[e]. NDVI: Normalized Difference Vegetation Index; categorized into tertiles.
[f]. Population density derived in 5,000 m buffers around residences and categorized into tertiles.
[g]. Low: categories 0 and 1 (no annoyance at all when the window is open); Medium:
categories 2 to 5; High: categories 6 to 10 (strong or unbearable annoyance).
[§]. Mean ± SD.
[¶]. Median (IQR).
*indicates statistically significant difference at the 5 % level between the Munich and Wesel areas.

nature reserve promoted a greater initial BP decline and lower BP during walking compared to conducting these same tasks in urban surroundings. A recent review, which summarized the findings of the beneficial effects of "Shinrin-yoku" (taking in the atmosphere of the forest) on BP [9], reported results from twenty-four field experiments conducted across Japan among 280 young adults. This review stated that forest environments promote lower systolic and diastolic BP compared to city environments [9]. Li et al. [8] reported that a day trip to the forest park in Tokyo, Japan, reduced the BPs of 16 male participants. Finally, viewing nature scenes prior to a stressor efficiently decreased BP during the recovery period in 23 participants from Great Britain, a result which also demonstrates a potential buffering effect of greenness [7]. All aforementioned studies have reported positive effects of green spaces and greenness on BP. Together, their findings on BP and other physiological measures (heart rate, heart rate variability, cortisol levels) confirm that exposure to nature induces parasympathetic activity during the recovery from a stressor, which is consistent with the psychoevolutionary theory suggested by Ulrich [6]. Despite the lack of similar experimental studies on children, as well as any evidence from observational studies, we hypothesize that the observed association between residential greenness and BP

Table 2 Associations between residential greenness, defined using Normalized Difference Vegetation Index (NDVI), and systolic and diastolic blood pressure

		Systolic blood pressure			Diastolic blood pressure		
Model	**NDVI[a]**	**ß[b]**	**SE[c]**	**p-value**	**ß[b]**	**SE[c]**	**p-value**
Crude[d]	*Low*	**1.07**	**0.53**	**0.043**	**0.80**	**0.39**	**0.041**
	Moderate	**1.32**	**0.53**	**0.012**	**1.01**	**0.39**	**0.010**
	High	ref.	-	-	ref.	-	-
Adjusted[e]	*Low*	0.90	0.50	0.073	**0.80**	**0.38**	**0.033**
	Moderate	**1.23**	**0.50**	**0.014**	**0.96**	**0.38**	**0.011**
	High	ref.	-	-	ref.	-	-
Temperature-adjusted[f]	*Low*	0.83	0.50	0.098	**0.83**	**0.38**	**0.027**
	Moderate	**1.12**	**0.50**	**0.025**	**1.00**	**0.38**	**0.008**
	High	ref.	-	-	ref.	-	-
Altitude-adjusted[g]	*Low*	0.79	0.50	0.115	0.71	0.38	0.061
	Moderate	**1.16**	**0.50**	**0.021**	**0.90**	**0.38**	**0.017**
	High	ref.	-	-	ref.	-	-
Urbanisation-adjusted[h]	*Low*	0.82	0.53	0.125	0.73	0.40	0.069
	Moderate	**1.11**	**0.52**	**0.032**	**0.87**	**0.39**	**0.024**
	High	ref.	-	-	ref.	-	-
$PM_{2.5}$ –adjusted[i]	*Low*	0.73	0.52	0.161	**0.93**	**0.39**	**0.017**
	Moderate	**1.13**	**0.51**	**0.026**	**1.03**	**0.38**	**0.007**
	High	ref.	-	-	ref.	-	-
PM_{10} –adjusted[j]	*Low*	0.96	0.54	0.074	**1.15**	**0.40**	**0.004**
	Moderate	**1.26**	**0.51**	**0.014**	**1.14**	**0.38**	**0.003**
	High	ref.	-	-	ref.	-	-
NO_2 –adjusted[k]	*Low*	0.85	0.54	0.118	**1.01**	**0.41**	**0.014**
	Moderate	**1.20**	**0.52**	**0.021**	**1.08**	**0.39**	**0.006**
	High	ref.	-	-	ref.	-	-
Noise annoyance-adjusted[l]	*Low*	0.90	0.50	0.074	**0.80**	**0.38**	**0.034**
	Moderate	**1.23**	**0.50**	**0.015**	**0.97**	**0.38**	**0.011**
	High	ref.	-	-	ref.	-	-

[a]. Greenness tertiles are area-specific. Munich: Low (NDVI < 0.307), Moderate (0.307 ≤ NDVI < 0.377), High (NDVI ≥ 0.377). Wesel: Low (NDVI < 0.382), Moderate (0.382 ≤ NDVI < 465), High (NDVI ≥ 0.465).
[b]. ß: Regression coefficient.
[c]. SE: Standard error.
[d]. Crude model is adjusted for study centre.
[e]. Adjusted model is adjusted for study centre, study, sex, age, BMI, season of BP measurements, parental education, and parental hypertension.
[f]. Temperature-adjusted model: Adjusted model and further adjustment for mean daily temperature on the day of BP measurements. The variable for the season of BP measurements has been removed.
[g]. Altitude-adjusted model: Adjusted model and further adjustment for altitude of residence. The variable for the study centre has been removed.
[h]. Urbanisation-adjusted: Adjusted model and further adjustment for study-specific tertiles of population density in a 5,000 m buffer around the residence.
[i]. $PM_{2.5}$-adjusted model: Adjusted model and further adjustment for $PM_{2.5}$ concentration at residence.
[j]. PM_{10}-adjusted model: Adjusted model and further adjustment for PM_{10} concentration at residence.
[k]. NO_2-adjusted model: Adjusted model and further adjustment for NO_2 concentration at residence.
[l]. Noise annoyance-adjusted model: Adjusted model and further adjustment for level of noise annoyance.
Bold text indicates statistical significance at the 5 % level.

in children in the current study is in line with this previous existing evidence and thus, with the psychoevolutionary theory. This is further supported by the fact that we also observed an association with pulse rate (PR) in the Munich study area (data not shown), although adjustment for this factor only slightly attenuated the risk estimates between greenness and BP. Despite the small effect sizes of the reported associations between greenness and BP in the current study (and in previous experimental studies), and thus the uncertain clinical impact,, our findings are

Table 3 Associations between residential greenness, defined using Normalized Difference Vegetation Index (NDVI), and systolic and diastolic blood pressure in Munich and Wesel study areas

		Munich (n = 1,256)						Wesel (n = 822)					
		Systolic blood pressure			Diastolic blood pressure			Systolic blood pressure			Diastolic blood pressure		
Model	NDVI[a]	ß[b]	SE[c]	p-value	ß	SE	p-value	ß	SE	p-value	ß	SE	p-value
Crude	*Low*	1.08	0.66	0.099	**1.06**	**0.51**	**0.039**	1.05	0.88	0.229	0.40	0.60	0.509
	Moderate	**2.33**	**0.66**	**< 0.001**	**1.47**	**0.51**	**0.004**	-0.21	0.88	0.814	0.31	0.60	0.609
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
Adjusted[d]	*Low*	1.02	0.63	0.106	**1.08**	**0.50**	**0.030**	0.63	0.80	0.435	0.47	0.57	0.411
	Moderate	**2.22**	**0.63**	**< 0.001**	**1.46**	**0.50**	**0.004**	-0.26	0.80	0.746	0.22	0.57	0.696
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
Temperature-adjusted[e]	*Low*	0.96	0.63	0.128	**1.05**	**0.50**	**0.035**	0.60	0.80	0.453	0.56	0.57	0.324
	Moderate	**2.19**	**0.63**	**0.001**	**1.43**	**0.50**	**0.004**	-0.46	0.80	0.564	0.37	0.57	0.516
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
Altitude-adjusted[f]	*Low*	0.68	0.66	0.304	0.97	0.52	0.063	0.62	0.81	0.443	0.45	0.57	0.433
	Moderate	**2.01**	**0.64**	**0.002**	**1.39**	**0.51**	**0.006**	-0.29	0.80	0.719	0.17	0.57	0.764
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
Urbanisation-adjusted[g]	*Low*	0.95	0.66	0.149	**1.03**	**0.52**	**0.049**	0.56	0.87	0.517	0.40	0.62	0.521
	Moderate	**2.09**	**0.66**	**0.001**	**1.36**	**0.52**	**0.009**	-0.37	0.82	0.649	0.17	0.58	0.767
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
$PM_{2.5}$ –adjusted[h]	*Low*	0.96	0.63	0.130	**1.16**	**0.50**	**0.021**	0.37	0.95	0.693	0.35	0.67	0.601
	Moderate	**2.18**	**0.64**	**0.001**	**1.53**	**0.50**	**0.002**	-0.41	0.83	0.624	0.17	0.59	0.773
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
PM_{10} –adjusted[i]	*Low*	1.20	0.66	0.068	**1.38**	**0.52**	**0.008**	0.41	1.02	0.687	0.97	0.72	0.179
	Moderate	**2.33**	**0.64**	**< 0.001**	**1.64**	**0.51**	**0.001**	-0.39	0.84	0.645	0.42	0.60	0.483
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
NO_2 –adjusted[j]	*Low*	1.08	0.67	0.110	**1.36**	**0.53**	**0.011**	0.66	0.93	0.481	0.38	0.66	0.566
	Moderate	**2.26**	**0.65**	**0.001**	**1.65**	**0.52**	**0.001**	-0.28	0.83	0.735	0.18	0.59	0.762
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-
Noise annoyance-adjusted[k]	*Low*	1.02	0.63	0.106	**1.06**	**0.50**	**0.033**	0.70	0.81	0.385	0.49	0.57	0.387
	Moderate	**2.18**	**0.63**	**0.001**	**1.44**	**0.50**	**0.004**	-0.20	0.81	0.806	0.21	0.57	0.711
	High	ref.	-	-	ref.	-	-	ref.	-	-	ref.	-	-

[a]. Greenness tertiles are different in Munich and Wesel areas. Munich: Low (NDVI < 0.307), Moderate (0.307 ≤ NDVI < 0.377), High (NDVI ≥ 0.377). Wesel: Low (NDVI < 0.382), Moderate (0.382 ≤ NDVI < 465), High (NDVI ≥ 0.465).
[b]. ß: Regression coefficient.
[c]. SE: Standard error.
[d]. Adjusted model is adjusted for study, sex, age, BMI, season of BP measurements, parental education and parental hypertension.
[e]. Temperature-adjusted model: Adjusted model and further adjustment for mean daily temperature on the day of BP measurements. The variable for the season of BP measurements has been removed.
[f]. Altitude-adjusted model: Adjusted model and further adjustment for altitude of residence.
[g]. Urbanisation-adjusted model: Adjusted model and further adjustment for tertiles of population density in a 5,000 m buffer around the residence.
[h]. $PM_{2.5}$-adjusted model: Adjusted model and further adjustment for $PM_{2.5}$ concentration at residence.
[i]. PM_{10}-adjusted model: Adjusted model and further adjustment for PM_{10} concentration at residence.
[j]. NO_2-adjusted model: Adjusted model and further adjustment for NO_2 concentration at residence.
[k]. Noise annoyance-adjusted model: Adjusted model and further adjustment for level of noise annoyance.
Bold text indicates statistical significance at the 5 % level.

nonetheless valuable as they provide further evidence of the biological mechanisms linking green vegetation exposure to health.

We are not able to explain why moderate levels of greenness appeared to increase BP more than low levels of greenness. It can be assumed that high greenness might stand for very green surroundings, low for built areas and moderate for a mixed land use. One can thus speculate that a neighbourhood without any vegetation whatsoever may not be attractive for children, which may bias the estimates. Future research is needed to determine whether this hypothesis is true.

In the analyses stratified by study area, associations between greenness and BP were only significant in the more urbanised Munich study area. This result might indicate that children living in urban regions, which generally lack vegetation, might benefit more from high residential greenness than children living in rural areas. Our findings may thus be especially relevant for policy makers and urban planners designing urban environments. Several previous studies have also reported that the degree of urbanisation may have a modifying effect on associations between green spaces and health benefits [39,40]. Our research group also recently observed differential associations between greenness and allergic outcomes in the same two study areas included in the current analysis [31].

Limitations

Given the general lack of studies investigating the influence of greenness on BP (specifically, in children), the results of this cross-sectional study should be interpreted cautiously. Causality cannot be inferred and the observed associations may be due to chance or residual confounding, especially given the null findings observed for the Wesel study area. However, associations were similar after controlling for several environmental stressors and when greenness levels were assessed using alternative satellite images taken during cloud-free days in 2006. Due to loss of follow-up over time of the birth cohorts, there is also a potential for selection bias. Families with a lower level of education and income were less likely to participate in the 10 year follow-up. Thus, children with a lower socioeconomic status (SES) are under-represented in this analysis. Nevertheless, we cautiously adjusted our models for parental education level, which represents SES. In our study, we used the common vegetation indicator NDVI to objectively estimate residential greenness. NDVI does not allow different types of vegetation to be distinguished and is sensitive to atmospheric effects, clouds and types of soil [17]. Also, the Landsat 5 TM satellite imagery is only accurate at a resolution of 30 m, which may not allow small scale effects of greenness on BP to be captured. A further limitation is that although three repeated BP readings are usually recommended [32], only two were available for this study population. Moreover, using automated cuffs can overestimate BP in children [41]. Nevertheless, the BP measurement protocol used for this study population was the same as used in the German population-based German Health Interview and Examination Survey for Children and Adolescents (KiGGS 2003–2006) survey [23]. Finally, we were unable to control for area level socioeconomic indicators, greenness levels around schools, indoor greenness (i.e. houseplants), other physiological measurements (e.g., heart rate variability, cortisol), psychological state and fitness of children and the time the children spent outdoors in their neighbourhood, and how the children may use their neighbourhood (which activities), all of which might represent sources of residual confounding.

Conclusions

Lower residential greenness was positively associated with higher BP in 10 year old German children. This association was independent from potential additional effects of environmental stressors. We recommend this association be further investigated in both children and adults and in different geographical areas that vary in urbanisation level. Area-level SES information and time spent in the neighbourhood should also be considered.

Additional file

Additional file 1: Figure S1. GAM-plots for the associations between residential greenness (NDVI) and blood pressure. Models adjusted for study, sex, age, BMI, season of BP measurements, parental education, parental hypertension and study centre **(A and D)**.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

IM conducted the GIS work for the Munich study area, analyzed the data and wrote the paper. ET assisted with the data analyses and the interpretation of the results, and critically revised the manuscript. EF assisted with the interpretation of the results and critically revised the manuscript. DS conducted GIS work for the Wesel study area. DB, SK, AvB and CPB have made substantial contributions to the conception, design and acquisition of the data. JH has made substantial contributions to the conception, design and acquisition of the data and supervised the work. All authors read and approved the final manuscript.

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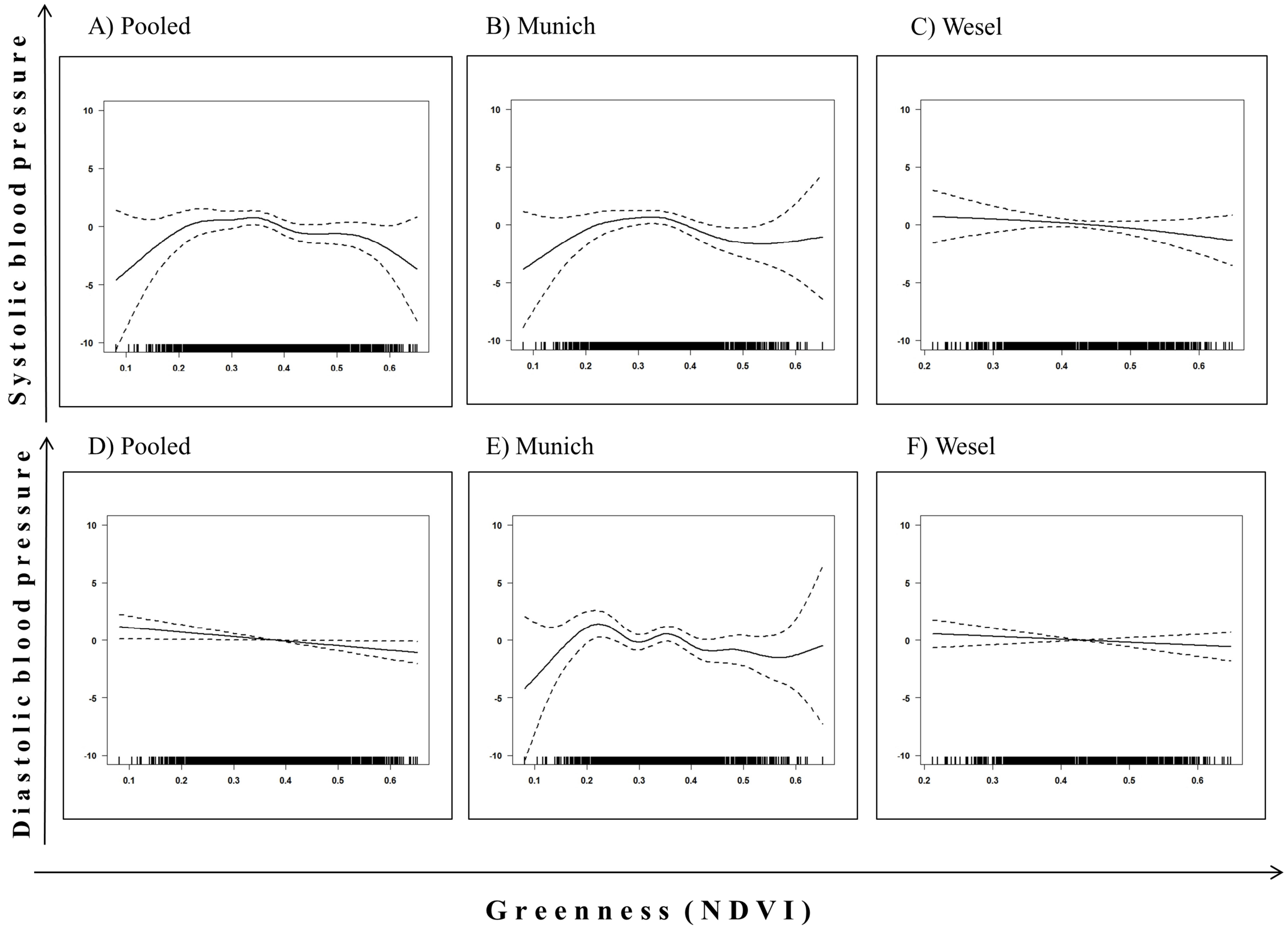
Paper 3: Supplementary Material



Additional figure 1 GAM-plots for the associations between residential greenness (NDVI) and blood pressure.
Models adjusted for study, sex, age, BMI, season of BP measurements, parental education, parental hypertension and study centre (A and D).

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Markevych I, Thiering E, Fuertes E, Sugiri D, Berdel D, Koletzko S, von Berg A, Bauer CP, Heinrich J: **A cross-sectional analysis of the effects of residential greenness on blood pressure in 10-year old children: Results from the GINIplus and LISAplus studies.** *BMC Public Health* 2014, **14**:477.

Markevych I, Fuertes E, Tiesler CMT, Birk M, Bauer CP, Koletzko S, von Berg A, Berdel D, Heinrich J: **Surrounding greenness and birth weight: Results from the GINIplus and LISAplus birth cohorts in Munich.** *Health Place* 2014, **26**:39–46.

Further publications:

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* These authors contributed equally to this work.

Erklärung

Hiermit erkläre ich, Iana Markevych, dass ich die vorliegende Dissertation selbstständig angefertigt habe. Ich habe mich außer der angegebenen keiner weiterer Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen. Ich habe bisher noch keinen Promotionsversuch unternommen, und die vorliegende Dissertation wurde nicht in gleicher oder ähnlicher Form bei einer anderen Stelle zur Erlangung eines akademischen Grades eingereicht.

München,

Iana Markevych