

Research Paper

How effective are greenbelts at mitigating urban sprawl? A comparative study of 60 European cities

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HIGHLIGHTS

- This study compares urban sprawl between cities with and without greenbelts.
- Greenbelts have been largely effective at reducing urban sprawl.
- The effect was somewhat stronger in cities of larger population sizes.
- The main mechanism was a reduction of land uptake per person, i.e., densification.
- We recommend greenbelts for de-sprawling strategies toward more compact green cities.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:

Built-up areas
Dispersion
Europe
Land uptake
Monitoring
Urban development
Urban growth
Urban growth management strategies
Utilization density
Weighted Urban Proliferation (WUP)
Weighted Sprawl per Capita (WSPC)

ABSTRACT

As Europe takes continuous steps towards urbanization, many cities in this continent are affected by the negative repercussions caused by urban sprawl. Among the efforts adopted to overcome urban sprawl and its adverse impacts is the greenbelt policy which is highly popular in several European countries. However, the actual effectiveness of this urban growth management strategy has been disputed. Using a sample of 60 European cities, 30 of which have greenbelts, this study compares (1) changes in urban sprawl in a 9-year time period (2006–2015), and (2) the level of sprawl between the cities with and without greenbelt in 2006 and 2015 separately, to investigate the performance of the greenbelts, applying the metrics of Weighted Urban Proliferation (WUP) and Weighted Sprawl per Capita (WSPC). The results show that (1) greenbelts have been largely effective at slowing down urban sprawl; and in most cases, they have helped reduce sprawl; (2) while urban sprawl decreased also in some cities without greenbelt, the average relative decrease in sprawl was much stronger in cities with greenbelts; (3) greenbelts were somewhat more beneficial in limiting urban sprawl in cities with larger population sizes; (4) the effectiveness of greenbelts was mainly due to the reduction of land uptake per person, i.e., through densification of the built-up areas. These findings are useful to inform future de-

Abbreviations: DIS, Dispersion of built-up areas; HP, Horizon of perception; LUP, Land uptake per person; PBA, Percentage of built-up areas; UPU / (inh. or job), Urban permeation units per inhabitant or job; UPU / m², Urban permeation units per square meter; WSPC, Weighted sprawl per capita; WUP, Weighted urban proliferation.

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<https://doi.org/10.1016/j.landurbplan.2022.104532>

Received 17 January 2022; Received in revised form 6 June 2022; Accepted 28 July 2022

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sprawling strategies in urban and regional planning as well as the formulation of new scenarios and of targets and limits to urban sprawl in support of more sustainable forms of urban development.

1. Disputed effectiveness of greenbelts

Unrestrained development of urban areas has been highly criticized globally because of current unsustainable trends and many adverse consequences (OECD, 2018; EEA & FOEN, 2016). The use of greenbelts is one of the measures that some countries have adopted to control urban sprawl which refers to dispersed, low-density development on undeveloped land (Han, 2019; Schulze Baing, 2010; Hack, 2012; Kovács et al., 2019). A greenbelt is identified as a perpetual open space, such as a forest or farmland enclosing a city or a region that is designated to prevent excessive urban growth by prohibiting construction or strictly controlling the urban development that may still be allowed (Bengston & Youn, 2006). This definition includes four main characteristics: (1) physical open space, (2) protected and preserved, (3) embracing a city or region, (4) barrier to urban expansion. Several other definitions that have been proposed in the literature mention similar characteristics. The first greenbelt was established in London in the 1930s (Freestone, 2002; Han & Xu, 2017; Amati & Yokohari, 2007), inspired by Ebenezer Howard's "Garden Cities" of 1898 (see App. A for more detailed information).

Many planners and scholars have emphasized the significance of greenbelts. Regarding the efficacy of greenbelts, Keeble stated: "The overall success of these is far greater than the detailed local failures which have sometimes occurred" (Keeble, 1961, as cited in Amati, 2008, p. 6). However, while greenbelts are believed to be workable means of limiting physical expansion by their advocates, the effectiveness of this policy has been debated by various opponents. Anas et al. asserted: "Greenbelts are likely to spawn exurban development further out, which raises another set of issues for growth management" (Anas et al., 1998, p. 46), and Han argued that "there is evidence that restricting the land supply and development activity leads to escalated development pressures inside the greenbelt in some countries" (Han, 2019, p. 301).

To address this dispute between opposing arguments about the general (non-)effectiveness of greenbelts, this study investigates the potency of greenbelts at curbing urban sprawl in European cities of several population-size categories, using Weighted Urban Proliferation and Weighted Sprawl per Capita metrics. The focus of our study is on the city scale and on covering a wide range of population sizes, because it is the responsibility of the city to make decisions about land-use for this area, because many important demographic and socio-economic urban indicators are closely related to city size (Bettencourt et al., 2007), and because of better data availability than for other scales. The literature does provide some studies that evaluate the effectiveness of greenbelts as a growth-management policy, but this study is the first to do so using a substantial sample size of cities that have or do not have a greenbelt, respectively. There were multiple reasons for the selection of European cities:

- (1) Most of the literature related to urban sprawl focuses on either larger scales than cities, such as countries and NUTS-2 regions (e.g., EEA & FOEN, 2016; Siedentop et al., 2016; Siedentop & Fina, 2012), or on only a small number of cities that illustrate the situation of urban sprawl in case studies, which do not allow for generalizations (e.g., Han & Go, 2019; Xie et al., 2020).
- (2) The studies available about greenbelts have mainly analyzed cities or regions with greenbelts without comparing them to cities without this feature, i.e., no control sites.
- (3) Europe is among the most urbanized regions in the world with 74 % of the population living in urban areas in 2018 (United Nations, 2019); and an extensive part of Europe is affected by urban sprawl (Hennig et al., 2015). Moreover, most of the cities with

greenbelts are located in Europe, with greenbelts being particularly popular in Germany and the UK (Schulze Baing, 2010; Kovács et al., 2019).

Because several drivers of population growth of cities in developed countries such as job opportunities and the availability of various amenities (Duranton & Puga, 2014) may generally be stronger in cities of larger population size, it is reasonable to expect that larger cities experience stronger absolute population growth and stronger pressure for urban sprawl. This pressure would increase the need for implementing growth-management policies including greenbelts, which would then be likely to lead to a greater densification of the built-up areas (including the construction of high-rises), and probably more so than in smaller cities.

Our analysis covers a 9-year timeframe (2006–2015) and the start and end years separately. We hypothesized that

- (1) cities that have established greenbelts are generally less sprawled than cities without greenbelt;
- (2) urban sprawl has increased more slowly in cities that have greenbelts than in those without greenbelt;
- (3) and greenbelts are more effective at mitigating urban sprawl in cities with larger population sizes, i.e., the absolute and relative differences in the changes in urban sprawl (2006–2015) between cities with and without greenbelt will be more pronounced.

2. Methods

2.1. Study areas and delineation of the reporting units

We selected a sample of 60 European cities from 13 countries, 30 of which have greenbelts and 30 do not. The cities were selected by identifying 30 European cities with greenbelts and dividing them into four population-size categories using their populations of 2015 (Table 1), so that they are representative of European cities of differing sizes. The cities were identified using information available in the literature and on the internet as there is no list of cities that have a greenbelt available that could have served as a sampling frame. According to the four population-size categories, cities without greenbelt were selected correspondingly within the same countries, so that an equal distribution of cities with and without greenbelt would allow for a balanced comparison (Table 1). The minimum population size of cities to be considered was approximately 100,000 people.

The population data at the city level were procured from Eurostat's *City statistic (urb)* database provided by the European Commission, which defines a city as "a local administrative unit (LAU) where the majority of the population lives in an urban centre of at least 50,000 inhabitants" (Eurostat - European Commission, n.d.). In some cases in which the greenbelt was established around the greater city, the population of the greater city is used. The greater city denotes "an approximation of the urban centre when this stretches far beyond the administrative city boundaries" (Eurostat - European Commission, n.d.).

Since it was important for the cities without greenbelt to be in the same population-size categories as their counterparts with greenbelts, to be balanced among countries as much as possible, and to have no (or only very small) changes in their city boundaries throughout the years (App. B), simple random sampling and stratified random sampling were not feasible. However, using four population-size categories made our selection process somewhat similar to stratified random sampling regarding the two criteria of population size and country, and we would consider our sample to be representative.

2.2. Data sources and calculation process

Information about built-up areas was obtained from the *High Resolution Layers (HRL) Imperviousness Density (IMD)* dataset provided by the European Copernicus programme for the reference years of 2006 and 2015 (European Environment Agency, 2018), the longest period available at the time of the study (App. C). This dataset is produced from satellite imagery with a 20 m × 20 m pixel resolution. The impervious layers provide imperviousness values ranging from 0 % to 100 %. The threshold for separating built-up and non-built-up cells was set at 30 % as in the studies by Orlitová et al. (2012) and EEA & FOEN (2016). While built-up areas are defined as surfaces covered by man-made structures, excluding roads and railways, the HRL dataset includes motorways and some other large roads, which were impossible to remove (EEA & FOEN, 2016).

The population data and total numbers of jobs for each city were collected from Eurostat’s *City statistic (urb)* database (Eurostat - European Commission, 2020a). In order to distinguish the jobs into part-time and full-time jobs, data about part-time employment as a percentage of the total employment were obtained from Eurostat’s *Employment and unemployment (Labour force survey) (employ)* database at the country level (Eurostat - European Commission, 2020b). The average numbers of usual weekly hours of work for part-time and full-time workers provided for each country were used to calculate a conversion factor for converting the part-time jobs into their full-time equivalents (App. D). For the cities with missing data in the target years, the population sizes and jobs were estimated using linear interpolation between other years where possible. In some cases, they needed to be calculated using extrapolation based on the slope of increase in the following or previous years. Job data for the Polish cities were obtained from Local Data Bank

from Statistics Poland, Activity rate database for Polish Voivodeships (provinces) (Central Statistical Office of Poland, 2020). The city boundaries corresponding to the numbers of inhabitants and jobs were procured from Eurostat’s *urban audit* database (Eurostat - European Commission, 2020c), and the shapefiles or maps of the greenbelts were acquired from governmental open-data portals or by contacting planners working for the cities by email. Cities are usually administratively delimited, as argued by Schumacher and Deilmann (2019), which makes sense in terms of linking them to statistical data. However, there are some remarkable differences in the delineation of administrative boundaries of cities between different European countries. For example, English cities are usually quite narrowly delineated, while French cities are often generously demarcated.

2.3. Measurement of urban sprawl

Quantification of urban sprawl was performed using the Urban Sprawl Metrics (USM) toolset, a GIS tool available from the WSL website (Nazarnia et al., 2016b), which uses three sets of input data including a binary map of built-up areas (cells of size 20 m x 20 m), the map of the boundaries of reporting units, and the numbers of inhabitants and jobs corresponding to the reporting units (Nazarnia et al., 2016b).

The USM toolset applies the method of Weighted Urban Proliferation (Jaeger & Schwick, 2014) and Weighted Sprawl per Capita (Behnisch et al., 2022) to quantify the degree of urban sprawl. Weighted urban proliferation (*WUP*) is based on the understanding that the degree of urban sprawl increases when the amount of built-up areas in a landscape increases, if they become more dispersed, or uptake of land per inhabitant or job augments, i.e., lower density (Jaeger & Schwick, 2014). Accordingly, the *WUP* method combines three components including

Table 1

The population sizes and areas of the 60 European cities with and without greenbelt investigated in this study, ordered by population size (source: Eurostat).

Size categories (based on population)	Cities with greenbelt	Inhabitants (2015) (Eurostat)	Area (km ²) (Eurostat shapefiles)	Cities without greenbelt	Inhabitants (2015) (Eurostat)	Area (km ²) (Eurostat shapefiles)
Very large: >2,500,000	1 Rome, Italy	2,872,021	1283.5	1 Berlin, Germany	3,469,849	891.8
	2 Greater Manchester, UK	2,744,508	1277.3	2 Madrid, Spain	3,141,991	603.9
Large: >1,000,000	3 Vienna, Austria	1,791,803	413.3	3 Hamburg, Germany	1,762,791	747.1
	4 Budapest, Hungary	1,757,618	525.4	4 Warsaw, Poland	1,743,399	516.7
	5 Stockholm Greater City, Sweden	1,689,952	1379.7	5 Valencia, Spain	1,383,908	400.3
	6 Munich, Germany	1,429,584	310.9	6 Milan, Italy	1,337,155	181.7
	7 Brussels, Belgium	1,196,831	162.2	7 Lyon, France	1,066,305	219.8
Medium-Large: between 500,000 and 1,000,000	8 Cologne, Germany	1,046,680	407.3	8 Naples, Italy	978,399	118.7
	9 Tyneside, UK	843,434	406.6	9 Turin, Italy	896,773	130.6
	10 Zagreb, Croatia	799,999	640.0	10 Marseille, France	893,431	297.1
	11 Leeds, UK	770,230	551.6	11 Lodz, Poland	699,453	293.1
	12 Krakow, Poland	763,272	326.9	12 Seville, Spain	693,878	141.7
	13 Frankfurt, Germany	717,624	248.7	13 Zaragoza, Spain	664,953	973.3
	14 Oslo, Norway	647,676	453.3	14 Bordeaux, France	635,780	245.7
	15 Stuttgart, Germany	612,441	209.8	15 Glasgow, UK	602,990	175.5
	16 Dusseldorf, Germany	604,527	217.5	16 Dortmund, Germany	580,511	279.4
	17 Copenhagen, Denmark	583,349	91.1	17 Leipzig, Germany	544,479	298.5
Medium: between 96,000 and 500,000	18 Bradford, UK	529,666	367.1	18 Antwerp, Belgium	515,593	202.7
	19 Hanover, Germany	523,642	204.2	19 Nuremberg, Germany	501,072	184.0
	20 Bristol, UK	445,901	111.4	20 Bonn, Germany	313,958	142.3
	21 Bilbao, Spain	345,141	41.6	21 Verona, Italy	260,125	198.7
	22 Coventry, UK	341,407	98.7	22 Ghent, Belgium	253,914	157.0
	23 Nottingham, UK	316,585	74.7	23 Lubeck, Germany	214,420	212.8
	24 Münster, Germany	302,178	303.7	24 Uppsala, Sweden	209,705	2249.3
	25 Stoke-on-Trent, UK	251,338	92.6	25 Linz, Austria	196,127	95.1
	26 Vitoria-Gasteiz, Spain	243,918	277.1	26 Gyor, Hungary	129,372	174.5
	27 Rennes, France	215,366	50.1	27 Bruges, Belgium	118,335	139.2
	28 York, UK	205,648	271.1	28 Lund, Sweden	113,078	443.1
	29 Oxford, UK	158,786	45.4	29 Osijek, Croatia	106,610	175.0
	30 Cambridge, UK	129,711	40.4	30 Lincoln, UK	96,634	35.6

the percentage of built-up areas (*PBA*), the dispersion of the built-up areas (*DIS*), and land uptake per person (*LUP*). While *DIS* captures the spatial arrangement of the built-up areas in a landscape, *LUP* denotes the area each person occupies on average. Jobs are also taken into account because highly utilized office buildings are not considered as sprawled areas, but do not usually house inhabitants. Consequently, higher numbers of inhabitants and jobs in a built-up area will manifest in a lower land uptake per person (Jaeger & Schwick, 2014).

While *WUP* denotes how much sprawl exists in a landscape per area, weighted sprawl per capita (*WSPC*) indicates how much urban sprawl is associated on average with each job or individual living in the reporting unit (Behnisch et al., 2022). The two metrics are related according to the equation $WSPC = \frac{A_{reporting_unit}}{N_{inh+job}} \cdot WUP$. Both metrics are intensive metrics, meaning that they can be compared between landscapes regardless of their sizes (Jaeger, 2000).

Quantifying dispersion demands determining a maximum distance around each point within the built-up area up to which the pattern of built-up areas will be analyzed. This distance is referred to as the horizon of perception (*HP*) or cut-off radius (Jaeger et al., 2010b), i.e., every pair of points contributes to dispersion when located within one another's *HP*, and its contribution is higher when the points are farther apart. This analysis includes a *HP* buffer of 2 km around the city boundaries (as done in the European study EEA & FOEN, 2016).

After calculating the changes between 2006 and 2015 and between groups of cities with and without greenbelt, three statistical tests, including Kruskal-Wallis test (or a *t*-test where applicable), Mood's median test, and a binomial test of proportions, were implemented on the results to determine the effectiveness of greenbelts. Since great changes in some cases largely affected the mean values, we also studied the medians. To test the third hypothesis, we first ran regressions for the changes in urban sprawl as a function of population size, and then compared the slopes of the regression lines between the two groups of cities. Statistical analysis was also conducted on each of the three

components separately (*PBA*, *DIS*, *LUP*).

Our research consists of two separate analyses: (1) a "temporal change analysis" examined the increases or decreases of urban sprawl during the 9-year timeframe, and (2) a "comparison analysis" which was done twice, comparing the cities with and without greenbelt for two particular years (2006 and 2015).

2.4. City size adjustment for comparison of cities of differing sizes

Because *WUP* is an intensive metric, it can be applied to, and compared between, landscapes irrespective of their sizes. However, in some cases (e.g., Uppsala), the boundary of the city is located far from the built-up areas, whereas in other cases (e.g., Glasgow), the boundary runs closely along the built-up areas. Such differences convolute a fair comparison of the cities, because even when the population sizes and the amounts and spatial patterns of the built-up areas of two cities are the same, the *PBA* of the two cities will differ. In such a situation in which the sizes and patterns of built-up areas are similar in two cities, but their boundaries and area sizes differ, the value of *WUP* will be lower for the landscape of the city whose boundary is located farther away as a result of lower *PBA*. Therefore, we rescaled the boundaries to make the cities comparable on an equal footing. In contrast, *WSPC* relates to the number of inhabitants and jobs rather than the landscape and is not affected by changes in the boundaries.

For this purpose, we used the relationship between population size in 2015 and the city size (log-transformed) applying linear regression to determine average city size as a function of population size, which we called "adjusted city size" (Fig. 1). In the cases in which the adjusted city size was greater than the original area, this step corresponds to adding some empty space with no built-up areas and no population. Hence, the only component adjusted is *PBA*, while *DIS* and *LUP* remain the same. The adjusted city size was larger than the size of the built-up areas in all cases. Consequently, none of the cities for which the area shrank due to the adjustment lost any built-up areas, i.e., its boundaries are simply

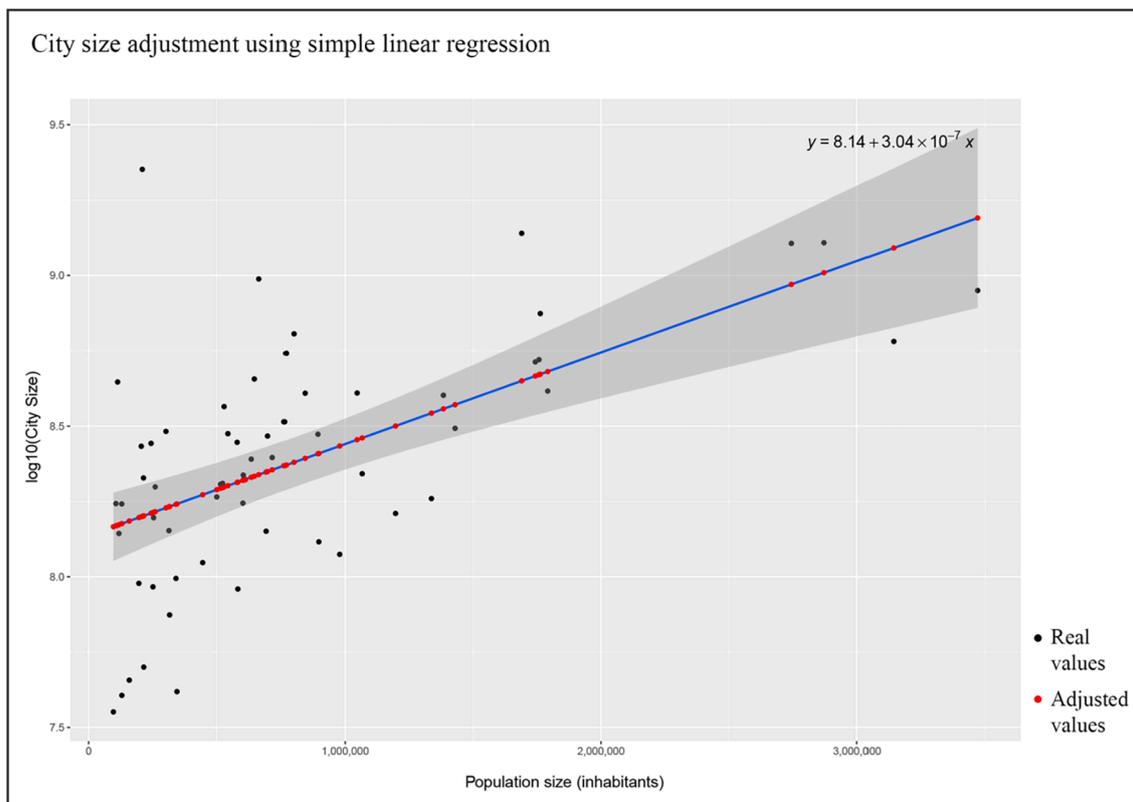


Fig. 1. City size adjustment: Average city size as a function of population size ($R^2 = 0.35$).

drawn somewhat closer around the built-up areas, and population stayed the same as well. The same adjusted city size was applied for both years. The corresponding values of the metrics are referred to as adjusted *PBA* and adjusted *WUP*. The adjustment was only applied for the comparison analysis. It was not needed for the change analysis since the cities were compared to themselves, and the boundaries stayed the same when we calculated the changes.

3. Results

3.1. Changes in urban sprawl between 2006 and 2015

3.1.1. Sprawl in relation to population: *WSPC*

The absolute and relative changes in *WSPC* between 2006 and 2015 differed significantly between the two groups of cities with and without greenbelt (Table 2). The absolute average contribution per person to urban sprawl decreased almost three times as strongly in cities with greenbelts than those without: The decrease was 97.0 UPU/(inh. or job) in cities without greenbelt, while it was 273.0 UPU/(inh. or job) in cities with greenbelts. The average relative changes in cities with and without greenbelt were in opposite directions, showing that the average contribution per person to urban sprawl increased by 24.2 % in cities without greenbelt, while it decreased by 27.3 % in cities with greenbelts (Table 2). This difference in direction between the average absolute and relative changes is mainly due to a few large absolute reductions in *WSPC* values in specific cases, as well as small relative decreases or great relative increases in *WSPC* values in the cities without greenbelt, which together led to an overall average relative increase in *WSPC* (see more detailed explanation in Discussion). The relative changes were statistically more significant than the absolute changes.

The medians of both absolute and relative changes in *WSPC* were positive in the cities without greenbelt and negative in the cities with greenbelts, i.e., *WSPC* increased (absolutely and relatively) between 2006 and 2015 in at least half of the cities without greenbelt, but decreased in more than half of the cities with greenbelts.

These findings were also supported by a test of proportions. The proportion of cities in which *WSPC* decreased differed significantly between the two groups of cities, with 90 % of the 30 cities with greenbelts, i.e., more than twice that of the cities without greenbelt with only 43 %. Among all the cities in which *WSPC* diminished, the relative decrease was significantly stronger in the cities with greenbelts (35.6 %) than in those without (17.6 %). However, the average absolute change in these cities was larger in the cities without greenbelt (-532.1 UPU/(inh. or job)) than with greenbelts (-306.9 UPU/(inh. or job)), because very high

absolute decreases in a few cities without greenbelt (such as Antwerp, Lincoln, and Leipzig) strongly affected the mean (Fig. 2). This difference, however, was not statistically significant (see in Apps. E and F).

3.1.2. Sprawl in relation to the landscape within city boundaries: *WUP*

Similar to the changes in *WSPC*, *WUP* decreased in 90 % of the cities with greenbelts, but only in 36.7 % of those without greenbelt (Fig. 3). Among the cities in which *WUP* decreased, the relative reduction was significantly stronger in those with greenbelts (30.8 %) than in those without (14 %). The differences in the changes in *WUP* between the two groups of cities were highly significant statistically. Between 2006 and 2015, the average level of urban sprawl decreased in both groups in absolute terms, but the average absolute decrease was almost four times stronger in cities with greenbelts: The mean in *WUP* decreased by 0.19 UPU/m² in the cities without greenbelt, whereas it was reduced by 0.72 UPU/m² in the cities with greenbelts. Similar to *WSPC*, the average relative change in *WUP* in cities with greenbelts was in the opposite direction of the average relative change in cities without greenbelt. While urban sprawl increased by 29.2 % in cities without greenbelt, it was reduced by 22.6 % in cities with greenbelts (Table 2).

As expected, the medians also followed this pattern in absolute and relative terms, with increases in the cities without greenbelt and decreases in the cities with greenbelts. In at least half of the cities without greenbelt, *WUP* advanced between 2006 and 2015, whereas it decreased in more than half of the cities with greenbelts.

To test hypothesis 3, we looked at the changes as a function of population size (Fig. 4). Comparing the differences in regression slopes for relative and absolute changes in *WSPC* and *WUP* using ANOVA, we found that the differences in slope were statistically significant for the relative changes (-0.0000076 %/inh. compared to 0.000042 %/inh. for *WSPC* ($p = 0.0105$) and -0.0000075 %/inh. compared to 0.000053 %/inh. for *WUP* ($p = 0.0051$)).

Among the cities in the very large and large population category, average *WSPC* decreased by 163.19 UPU/(inh. or job) in the cities with greenbelts, which was 7 times stronger than the decrease in the cities without greenbelt. In relative terms, *WSPC* decreased by 46.4 % in the cities with greenbelts. A similar pattern was observed for *WUP* with an absolute decrease by 0.47 UPU/m² and relative decrease by 41.4 % in the cities with greenbelts (App. G).

3.1.3. Changes in the three components: *LUP*, *PBA*, and *DIS*

The results of *LUP* were the strongest and were highly significant, revealing the most important cause of change in urban sprawl in cities with greenbelts (Table 3). While the average value of *LUP* decreased in

Table 2

Results of the statistical analysis on the absolute and relative changes in urban sprawl in the two groups of cities (** = highly significant: $p < 0.01$, * = significant: $0.01 < p < 0.05$, + = marginally significant: $0.05 < p < 0.1$).

Tests		Outputs	Changes in Urban Sprawl (2006 – 2015)			
			<i>WSPC</i> Absolute Changes (UPU per inhabitant or job)	<i>WSPC</i> Relative Changes (%)	<i>WUP</i> Absolute Changes (UPU per m ² of landscape)	<i>WUP</i> Relative Changes (%)
Kruskal-Wallis test	For differences between the means	<i>p</i> -value	0.012*	0.000018**	0.00019**	0.000005**
		Mean in group 1	-273.05	-27.27	-0.72	-22.64
		Mean in group 2	-97.02	24.17	-0.19	29.17
	For differences between the means of decreased values	<i>p</i> -value	0.15	0.029*	0.96	0.032*
		Mean in group 1	-306.91	-35.56	-1.08	-30.76
		Mean in group 2	-532.15	-17.61	-0.82	-14.00
Mood's Median test	For differences between the medians	<i>p</i> -value	0.010*	0.00034**	0.000042**	0.000042**
		Median in group 1	-172.04	-24.03	-0.43	-17.92
		Median in group 2	0.44	5.21	0.01	6.03
Binomial test of proportions	For differences between the proportions of cities with decreased values	<i>p</i> -value	0.00037**	0.00037**	0.000059**	0.000059**
		Proportion in group 1	0.90	0.90	0.90	0.90
		Proportion in group 2	0.43	0.43	0.37	0.37

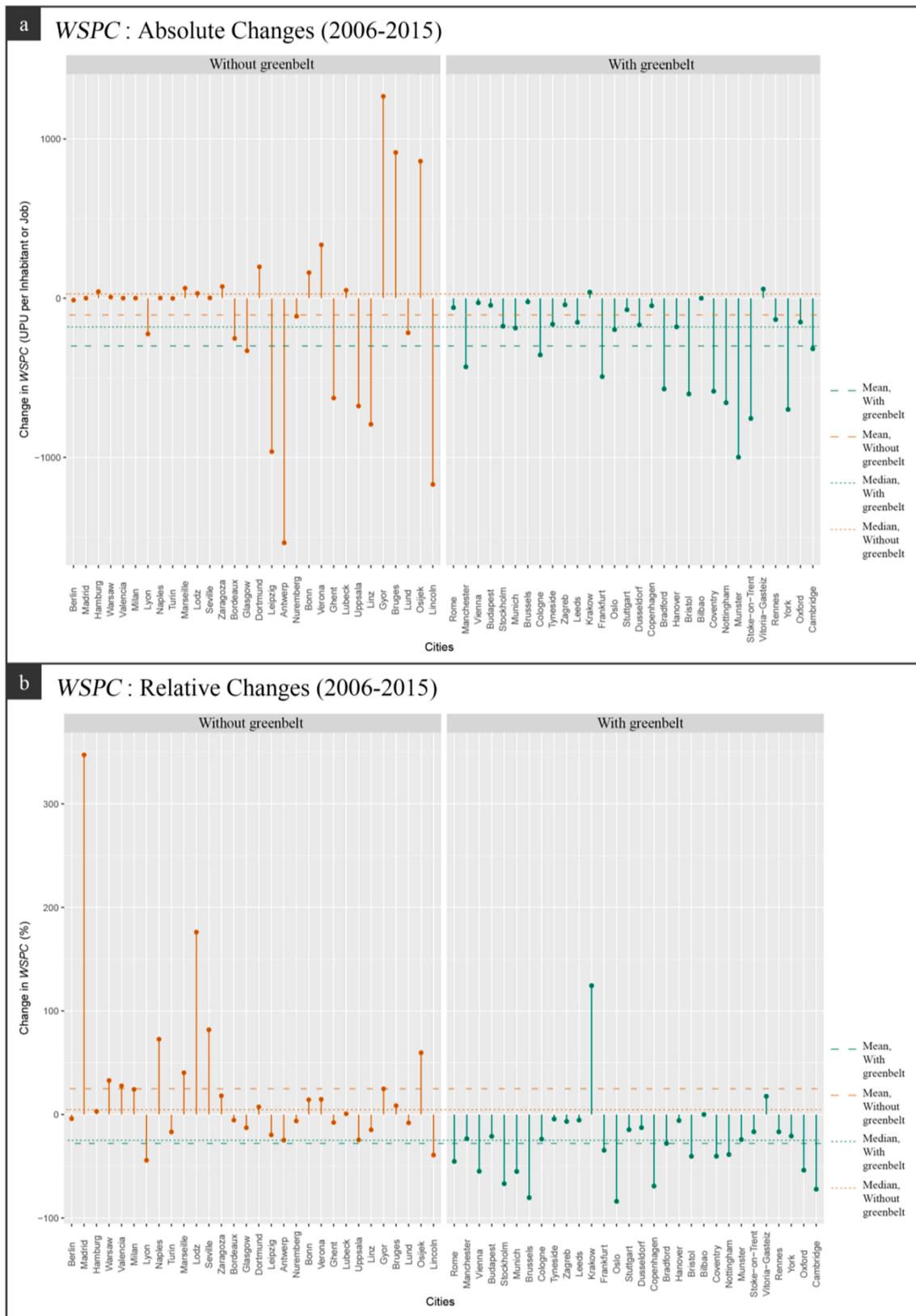


Fig. 2. Absolute (a) and relative changes (b) in WSPC in the cities without greenbelt (orange) and with greenbelts (green); cities sorted by population size in descending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both groups of cities, this decrease was 17 times higher in cities with greenbelts (-5.88 compared to $-0.35 \text{ m}^2 /(\text{inh. or job})$). In terms of relative changes, LUP decreased on average by 5.76 % in cities with

greenbelts, but increased by 0.55 % in cities without greenbelt. The difference between relative changes in LUP was statistically more significant compared to the absolute changes (Table 3).

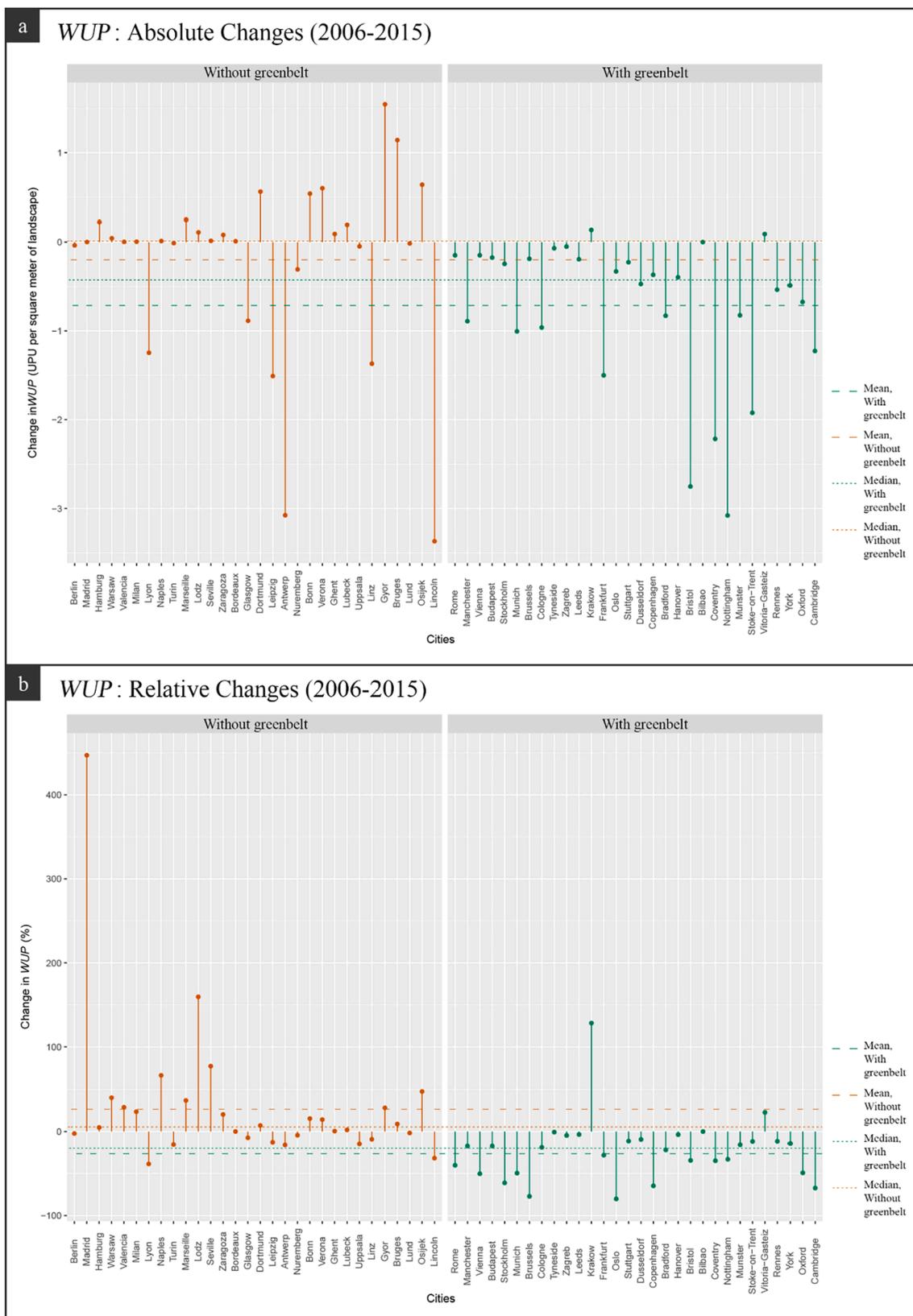


Fig. 3. Absolute (a) and relative changes (b) in WUP in the cities without greenbelt (orange) and with greenbelts (green); cities sorted by population size in descending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The difference between the median changes also was highly significant. The mid-value of changes in *LUP* was negative in the cities with greenbelts, while its counterpart in the cities without greenbelt still was

positive. The proportion of cities in which *LUP* decreased (90 %) was considerably greater in the group of cities with greenbelts; it decreased in only 43 % of those without (Fig. 5).

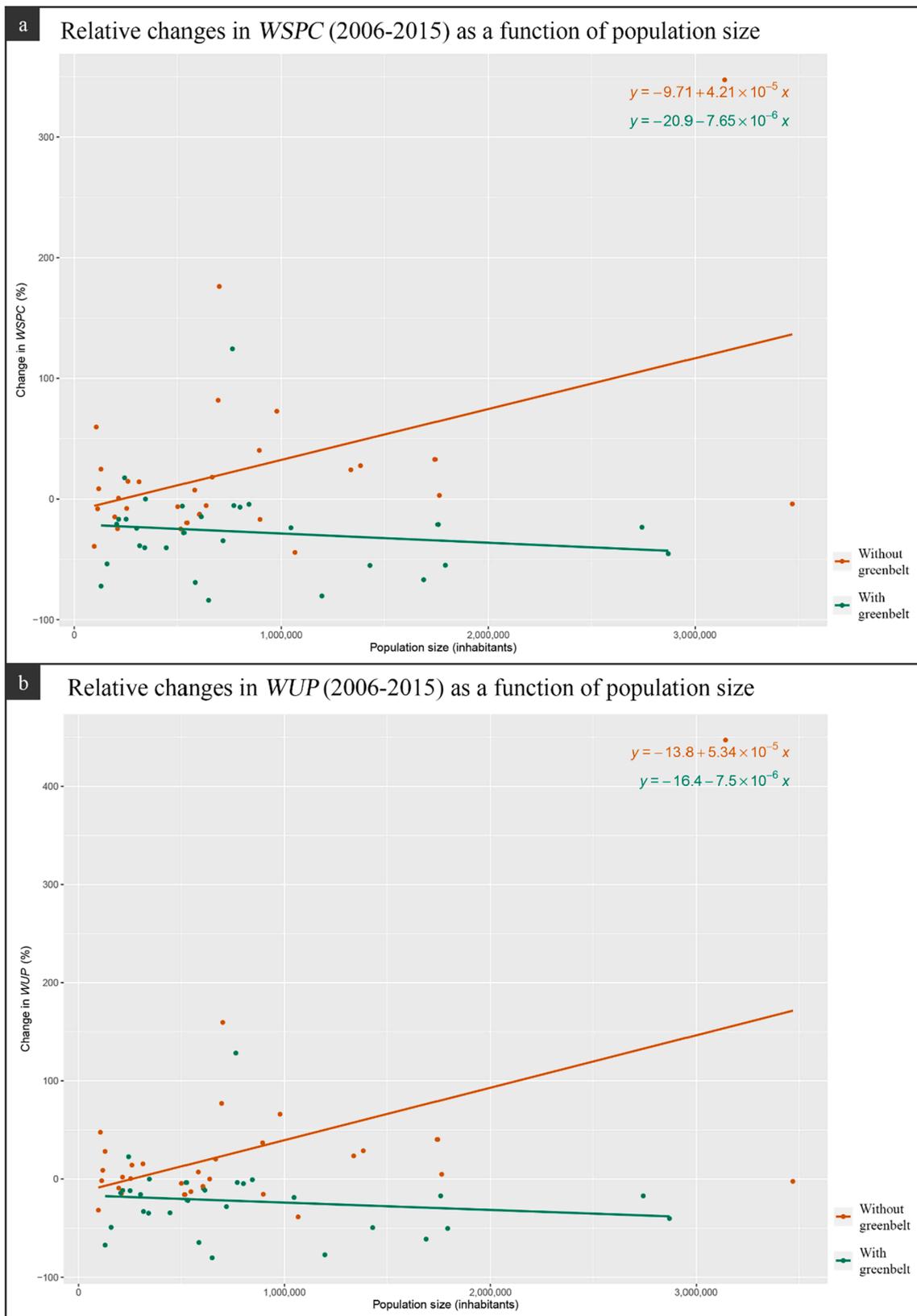


Fig. 4. Relative changes in (a) WSPC and (b) WUP in the cities without greenbelt (orange) and with greenbelts (green) as a function of population size (Orange: R^2 -WSPC = 0.22 and R^2 -WUP = 0.25; Green: R^2 -WSPC = 0.02 and R^2 -WUP = 0.02). See App. H for absolute changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In contrast, *PBA* and *DIS* did not show considerable differences between the two groups (Figs. 6 and 7). *PBA* demonstrated only a moderate influence on the differences in the changes in urban sprawl between the groups. Average *PBA* increased 1.77 times more strongly in the cities without greenbelt than in those with greenbelts in terms of relative changes, and this difference was statistically significant. Average changes in *DIS* were very small and exhibited modest increases in both groups of cities; they were slightly larger in the cities without greenbelt, but the difference was not statistically significant.

3.2. Comparison between the two groups of cities for each year separately

3.2.1. Urban sprawl in 2006 and 2015 using *WSPC* and adjusted *WUP*

The differences between the means (and the medians) of *WSPC* and adjusted *WUP* were considerable with much greater values in the cities without greenbelt than those with a greenbelt for 2006 and 2015 (App. I), but they were not statistically significant for the sample size available in this study (Table 4). This comparison covered a large range of population sizes and exhibited high variability in the values (App. I). Due to this large variability, a larger sample size would be needed to achieve statistical significance of the differences.

In contrast, the analysis of three population-size categories of cities resulted in statistically significant differences between the medium-sized cities (with <500,000 inhabitants) with and without greenbelt for both 2006 and 2015 (Table 5). Among the medium-sized cities, the mean *WSPC* value was lower (by 63 %) in the cities with greenbelts in 2006 (1679.8 UPU/(inh. or job) compared to 4509.3 UPU/(inh. or job)). In 2015, the average value of *WSPC* in the cities with greenbelts was remarkably lower as well (by 73 %), and the difference was even more statistically significant. The medians support these results as well, displaying statistically significant differences for both years. Similarly, the differences between the means of the adjusted *WUP* values, were marginally significant in 2006 and significant in 2015 in the medium-sized cities (and between the medians in 2015). In addition, the difference between the average values of adjusted *WUP* in the class of very large and large cities was marginally significant in 2006 (but not in 2015).

While the means (and medians) of *WSPC* and adjusted *WUP* were greater in the cities without greenbelt than in the ones with greenbelts for the medium-large cities in both years, the differences were not statistically significant, likely due to small sample size (10 cities in each group). A bigger sample size in this population-size category would be likely to exhibit statistically significant results.

In contrast, in the large and very-large city category, the average

level of sprawl was higher in the cities with greenbelts than those without greenbelt, and the difference in the mean values of adjusted *WUP* in 2006 was marginally significant. The significance of the difference, however, vanished in 2015, due to a greater reduction in the mean value of adjusted *WUP* in the cities with greenbelts. Although the average adjusted *WUP* also decreased in the cities without greenbelt, this decrease was much weaker than in those with greenbelts. The same pattern was observed for the median and mean differences in the *WSPC* values (see Discussion).

3.2.2. Components of urban sprawl in 2006 and 2015

The mean value of land uptake per person in 2015 was lower in the cities with greenbelts than in those without greenbelt with 94.9 m²/(inh. or job) and 111.8 m²/(inh. or job), respectively ($p = 0.085$) (Table 6).

The adjusted *PBA* was lower in the cities without greenbelt in both years, but it increased more strongly in the cities without greenbelt than in the cities with greenbelts (0.96 % compared to 0.64 %). At the current rates of increase, the adjusted *PBA* mean value in the cities without greenbelt would surpass the cities with greenbelts 41 years after 2015 (in 2056). *DIS* values were similar in both years, and while average *DIS* increased in the cities without greenbelt, it decreased in those with greenbelts.

The comparison of the three components for the three population-size categories also revealed significant differences for the medium-sized cities: The average *LUP* values differed significantly between the two groups of cities (Table 7). Since the differences in adjusted *PBA* and *DIS* were not significant for the medium-sized cities, it is fair to conclude that the differences in the overall sprawl values in 2006 and 2015 in this category were mostly the responses to major differences in *LUP*, i.e., denser built-up areas.

A marginally significant difference was observed for *LUP* in the large and very large cities category as well, which explains the differences between the sprawl values in 2006.

The analysis did not detect any statistically significant differences in adjusted *PBA* or *DIS* between cities with and without greenbelt for neither of the population-size categories.

4. Discussion

4.1. Changes in urban sprawl and its components

The greenbelts have been considerably effective in mitigating urban sprawl in Europe at the city level. Even though urban sprawl has increased unequivocally worldwide (OECD, 2018; EEA & FOEN, 2016;

Table 3

Results of the statistical analysis on absolute and relative changes in the three components of urban sprawl in the two groups of cities (** = highly significant: $p < 0.01$, * = significant: $0.01 < p < 0.05$, + = marginally significant: $0.05 < p < 0.1$).

Tests	Outputs	Changes in the Components of Urban Sprawl (2006 – 2015)					
		<i>PBA</i> Absolute Changes	<i>PBA</i> Relative Changes	<i>DIS</i> Absolute Changes	<i>DIS</i> Relative Changes	<i>LUP</i> Absolute Changes	<i>LUP</i> Relative Changes
	Group 1: with greenbelt Group 2: without greenbelt	(Percentage Point)	(%)	(UPU per m ² of built-up area)	(%)	(m ² per inhabitant or job)	(%)
Kruskal-Wallis test / t-test	p-value	0.21	0.014*	0.22	0.21	0.00089**	0.000083**
For differences between the means	Mean in group 1	0.50	1.83	0.0228	0.0474	-5.88	-5.76
	Mean in group 2	0.79	3.25	0.0318	0.0665	-0.358	0.55
Mood's Median test	p-value	0.61	0.12	0.31	0.31	0.0048**	0.00034**
For differences between the medians	Median in group 1	0.42	1.55	0.0148	0.0307	-6.80	-6.30
	Median in group 2	0.48	2.57	0.0197	0.0403	0.80	1.14
Binomial test of proportions	p-value	NA	NA	0.47	0.47	0.00037**	0.00037**
For differences between the proportions of cities with decreased values	Proportion in group 1	0	0	0.067	0.067	0.90	0.90
	Proportion in group 2	0	0	0	0	0.43	0.43

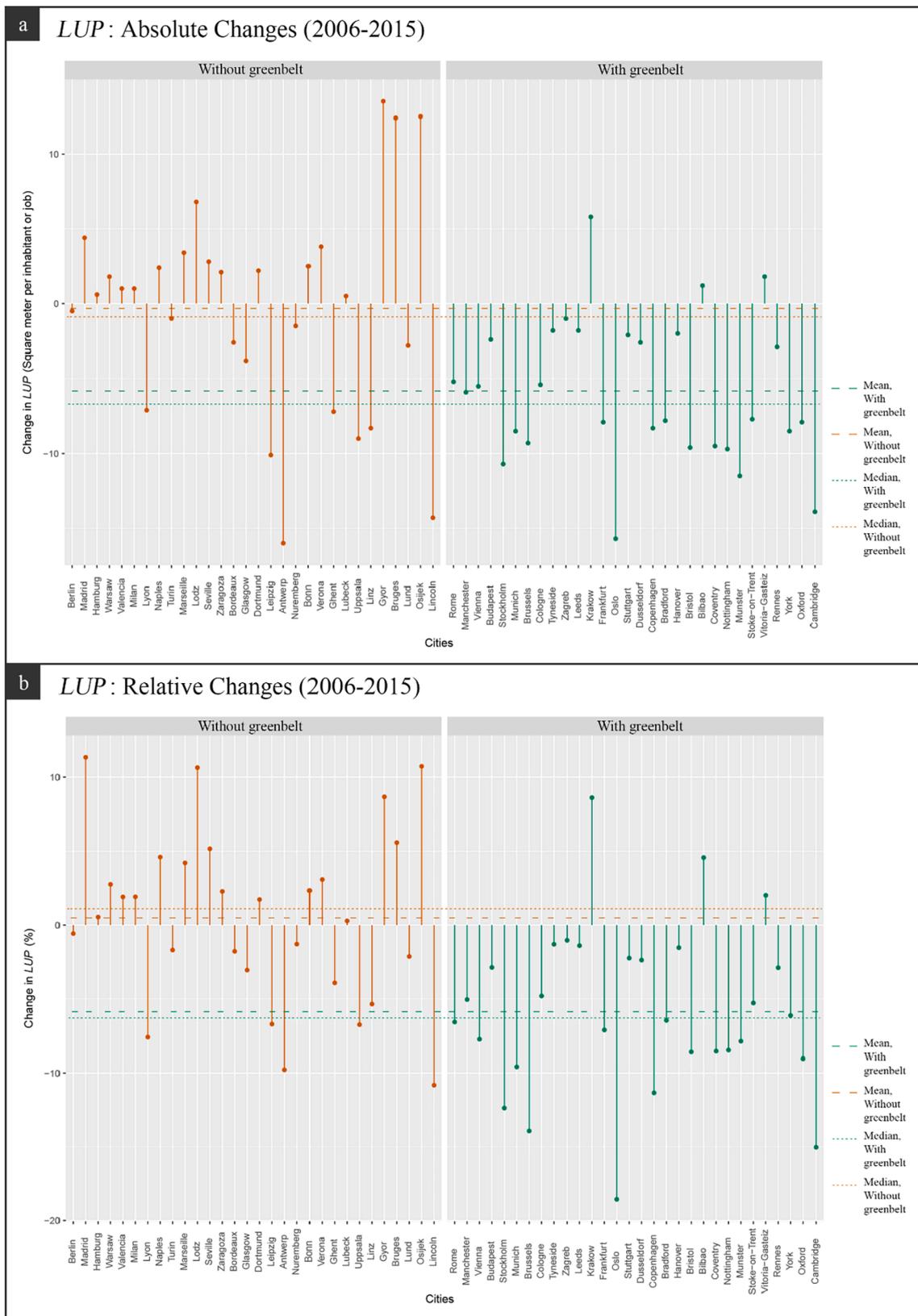


Fig. 5. Absolute (a) and relative changes (b) in LUP in the cities without greenbelt (orange) and with greenbelts (green); cities sorted by population size in descending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

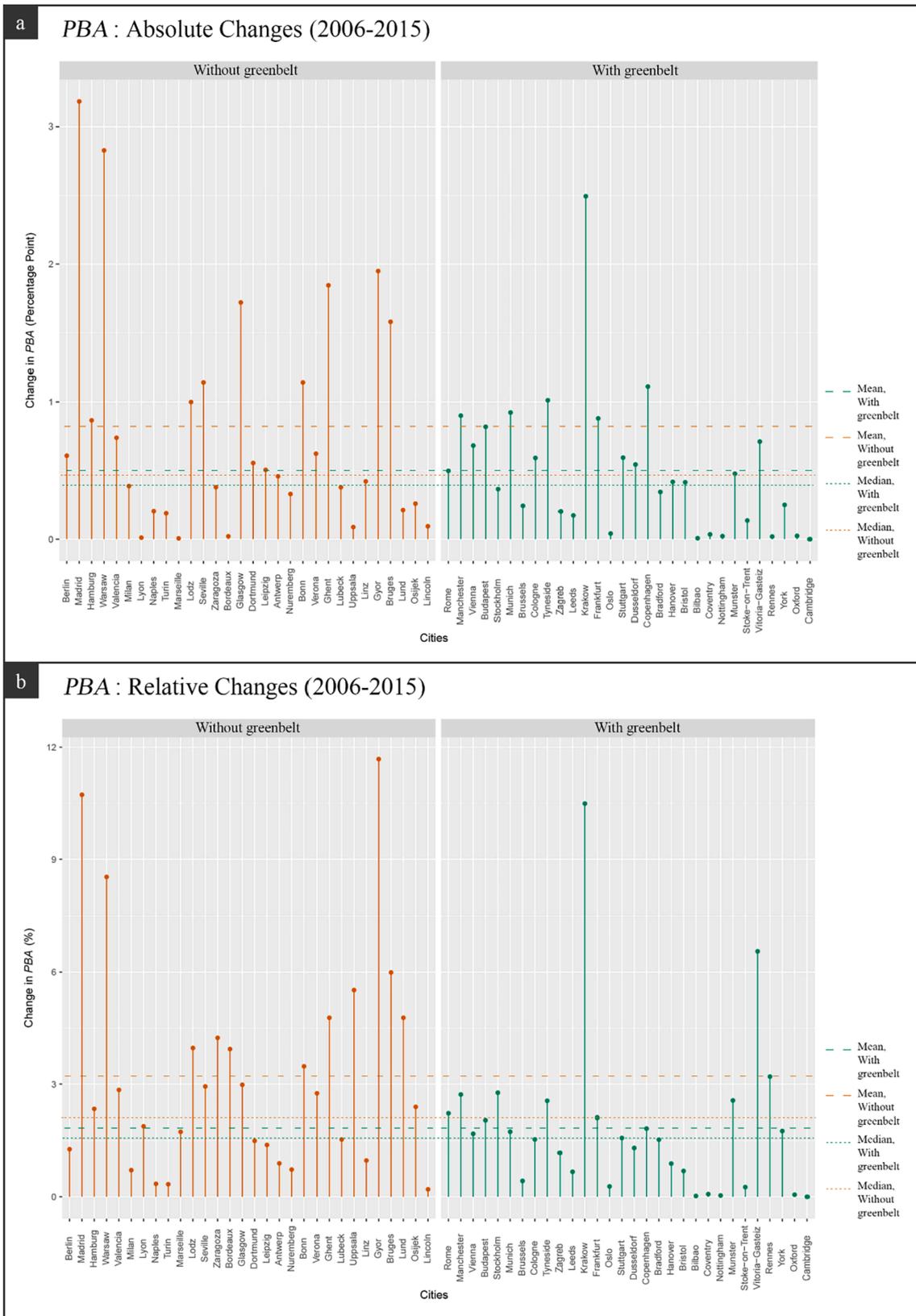


Fig. 6. Absolute (a) and relative changes (b) in PBA in the cities without greenbelt (orange) and with greenbelts (green); cities sorted by population size in descending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

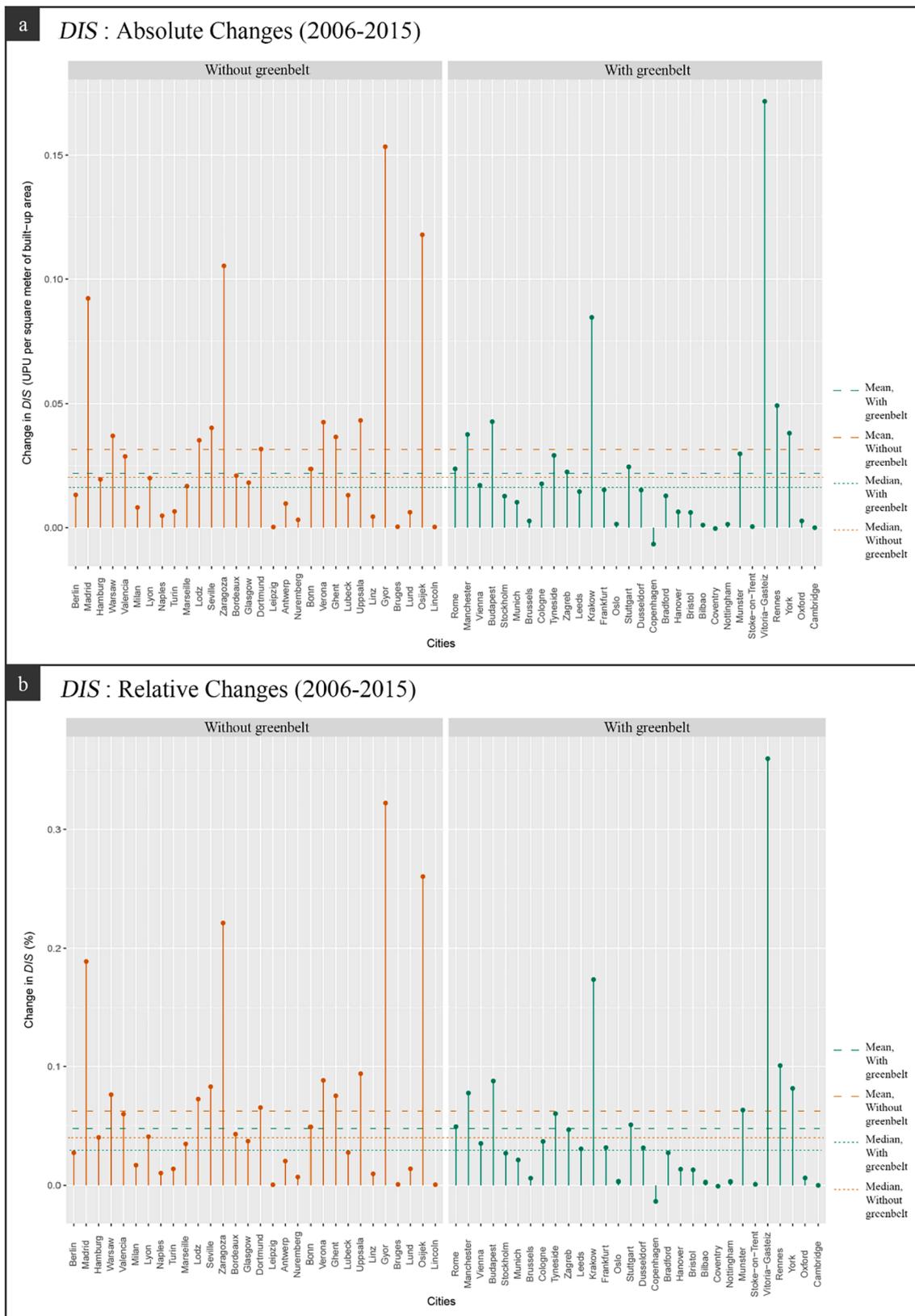


Fig. 7. Absolute (a) and relative changes (b) in DIS in the cities without greenbelt (orange) and with greenbelts (green); cities sorted by population size in descending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4

Results of the statistical analysis comparing the mean and median level of urban sprawl between the two groups of cities with and without greenbelt in 2006 and 2015 (** = highly significant: $p < 0.01$, * = significant: $0.01 < p < 0.05$, + = marginally significant: $0.05 < p < 0.1$).

Tests	Outputs	Urban Sprawl			
		WSPC (UPU per inhabitant or job)		Adjusted WUP (UPU per m ² of landscape)	
		2006	2015	2006	2015
Kruskal Wallis test	p-value	0.391	0.165	0.734	0.344
	Mean in group 1	1288.76	1015.715	4.16	3.54
For differences in the means	Mean in group 2	2504.65	2407.629	5.74	5.66
	p-value	0.306	0.1245	1	0.609
Mood's Median test	Median in group 1	708.77	620.9881	2.44	2.05
	Median in group 2	1617.11	1746.176	2.77	2.97

Behnisch et al., 2022), our results show that urban sprawl has decreased substantially in cities that have greenbelts. On average, sprawl per area as well as the average contribution per person to sprawl decreased between 2006 and 2015, absolutely and relatively, in these cities. In contrast, the relative changes in average WSPC and WUP indicated increases in urban sprawl in the cities without greenbelt. The mean absolute changes in WSPC and WUP, however, displayed minor decreases in the cities without greenbelt on average, i.e., remarkably weaker than the mean absolute decrease in the cities with greenbelts.

Two main reasons explain why average sprawl decreased in absolute terms, while it increased in relative terms in the cities without greenbelt: (1) Major absolute decreases in a few cities, namely Antwerp, Lincoln, and Leipzig, had a large effect on the mean values of WSPC and WUP, propelling the average absolute changes of these two metrics into the negative range; whereas (2) the relative decreases in sprawl in these cities and several other cities were small, while the relative increases in the other cities in this group were high, resulting in an overall average increase. In other words, the high 2006 values of WSPC and WUP in most cities without greenbelt led to low relative decreases even when WSPC and WUP strongly abated; contrarily, for some cases such as Madrid (where the 2006 values were quite low), even slight absolute increases resulted in large relative increases. In contrast, most of the cities with greenbelts had fairly low values in 2006, and most of them decreased by 2015, hence, division of these changes by the low values of 2006 resulted in rather large relative decreases.

The effectiveness of greenbelts at curbing urban sprawl is also evident in the proportions of cities in which WSPC and WUP decreased. Both metrics decreased in most cities with greenbelts as opposed to those without, and the average relative reductions were twice as strong in the cities with greenbelts.

To discover the reasons behind the success of greenbelts, we investigated the three components of WSPC and WUP, of which only LUP demonstrated strong average absolute and relative reductions as a result of stronger densification of the existing built-up areas in cities with greenbelts which had a stronger influence than the expansion of built-up areas. Smaller average relative increase in PBA also contributed to lower values of WSPC and WUP in these cities. Negligible changes in DIS seem sensible as the spatial arrangement of the existing buildings cannot be changed since they cannot easily be moved around to other locations.

The group of very large and large cities exhibited greater differences between the relative changes in the cities with and without greenbelt than the other two population-size categories. Regression of the changes

Table 5 Results of the statistical analysis comparing the level of urban sprawl between the two groups of cities in 2006 and 2015 for three population-size categories. The sample size for each group was 8 cities in the very large and large category, 10 cities in the medium-large category, and 12 cities in the medium category (** = highly significant: $p < 0.01$, * = significant: $0.01 < p < 0.05$, + = marginally significant: $0.05 < p < 0.1$).

Tests	Outputs	Urban Sprawl in different population size categories											
		WSPC (UPU per inhabitant or job)						Adjusted WUP (UPU per m ² of landscape)					
		2006		2015		2006		2015		2006		2015	
		Very Large and Large	Medium-Large	Medium	Medium-Large	Very Large and Large	Medium-Large	Medium	Medium-Large	Very Large and Large	Medium-Large	Medium	Medium-Large
Kruskal Wallis test / t-test	p-value	0.115	0.398	0.016*	0.376	0.0053**	0.974	0.087+	0.508	0.248	0.01975*	0.508	0.01975*
	Mean in group 1	545.50	1438.25	1679.83	1252.19	1239.90	5.99	3.61	5.48	1.81	2.88	5.48	2.88
	Mean in group 2	272.83	2123.17	4509.26	1865.77	4518.94	7.80	6.89	7.36	1.27	7.14	7.36	7.14
For differences in the means	p-value	0.333	0.677	0.037*	0.677	0.333	0.677	0.211	0.677	0.333	0.037*	0.677	0.037*
	Median in group 1	237.65	1325.63	1449.54	932.26	865.11	5.19	3.59	4.19	0.66	2.35	4.19	2.35
	Median in group 2	11.40	1791.76	2983.71	1678.30	2626.99	0.06	5.06	6.24	0.09	5.78	6.24	5.78

Table 6

Results of statistical analysis of the three components of urban sprawl in 2006 and 2015 (** = highly significant: $p < 0.01$, * = significant: $0.01 < p < 0.05$, + = marginally significant: $0.05 < p < 0.1$).

Tests	Outputs Group 1: with greenbelt Group 2: without greenbelt	Components of Urban Sprawl					
		2006			2015		
		Adjusted PBA (%)	DIS (UPU per m ² of built-up area)	LUP (m ² per inhabitant or job)	Adjusted PBA (%)	DIS (UPU per m ² of built-up area)	LUP (m ² per inhabitant or job)
Kruskal Wallis test / t-test	p-value	0.623	0.953	0.583	0.692	0.976	0.085 ⁺
For differences in the means	Mean in group 1	34.69	48.37	112.11	35.33	48.29	94.93
	Mean in group 2	32.94	48.26	100.81	33.90	48.40	111.76
Mood's Median test	p-value	0.306	1	0.306	0.306	1	0.1245
For differences in the medians	Median in group 1	33.85	48.52	98.70	35.44	48.55	96.75
	Median in group 2	28.51	48.54	116.35	28.96	48.57	116.30

Table 7

Results of statistical analysis of the three components of urban sprawl in 2006 and 2015 in different population size categories. The sample size for each group was 8 cities in the very large and large category, 10 cities in the medium-large category, and 12 cities in the medium category (** = highly significant: $p < 0.01$, * = significant: $0.01 < p < 0.05$, + = marginally significant: $0.05 < p < 0.1$).

Tests	Outputs Group 1: with greenbelt Group 2: without greenbelt	Components of Urban Sprawl					
		Adjusted PBA (%)					
		2006			2015		
		Very Large and Large	Medium-Large	Medium	Very Large and Large	Medium-Large	Medium
t-test	p-value	0.245	0.9225	0.832	0.272	0.934	0.716
For differences in the means	Mean in group 1	39.98	43.31	22.22	40.75	44.20	22.53
	Mean in group 2	32.96	42.83	23.03	34.00	43.79	23.95
Mood's Median test	p-value	0.333	0.677	0.677	0.333	0.677	0.677
For differences in the medians	Median in group 1	42.13	42.95	24.16	43.07	43.51	24.58
	Median in group 2	28.32	42.37	24.48	28.83	42.68	25.94
		DIS (UPU per m ² of built-up area)					
		2006			2015		
		Very Large and Large	Medium-Large	Medium	Very Large and Large	Medium-Large	Medium
t-test	p-value	0.318	0.433	0.156	0.299	0.402	0.158
For differences in the means	Mean in group 1	48.60	48.47	48.11	48.62	48.49	48.14
	Mean in group 2	48.82	48.61	47.50	48.85	48.64	47.54
Mood's Median test	p-value	0.333	0.677	0.677	0.333	0.677	0.677
For differences in the medians	Median in group 1	48.60	48.57	48.12	48.63	48.59	48.12
	Median in group 2	48.85	48.58	47.93	48.90	48.61	47.93
		LUP (m ² per inhabitant or job)					
		2006			2015		
		Very Large and Large	Medium-Large	Medium	Very Large and Large	Medium-Large	Medium
t-test	p-value	0.1 ⁺	0.888	0.0079 ^{**}	0.263	0.7295	0.0026 ^{**}
For differences in the means	Mean in group 1	88.12	105.05	105.78	81.51	105.42	98.67
	Mean in group 2	68.81	107.03	148.67	69.26	100.95	149.00
Mood's Median test	p-value	0.333	0.677	0.037 [*]	0.333	0.677	0.037 [*]
For differences in the medians	Median in group 1	85.05	109.60	111.20	78.00	103.20	101.70
	Median in group 2	58.70	116.20	133.30	60.65	114.70	129.00

as a function of population size also revealed that the greenbelts were more effective in controlling urban sprawl in cities of larger population sizes in terms of relative changes. This outcome confirmed our initial hypothesis 3 in terms of relative changes, while it did not provide evidence in terms of absolute changes.

It is noteworthy that the greenbelts were effective at reducing urban sprawl (both WSPC and WUP decreased) in all 8 cities with greenbelts in

the very large and large category, but in only 2 of the cities without greenbelt (25 %). The cities in the medium-size category also demonstrated significant results, but the differences between the cities with and without greenbelt were statistically more significant in the group of very large and large cities, even though sample size in this category was small.

It is important to keep in mind that because of differences in the

regulatory strength of greenbelts and other growth management policies, successful mitigation of urban sprawl may in some cases have been the result of a combination of land-use planning instruments rather than just the greenbelt.

4.2. Comparison of urban sprawl and its components for each year separately

Neither of the *WSPC* and adjusted *WUP* metrics provided statistically significant results for 2006 nor 2015 for the sample size available in this study, even though the average *LUP* value demonstrated a marginally significant difference in 2015. However, there were large differences as predicted by hypothesis 1, i.e., greater values in cities without greenbelt. Considering that the variability between cities was substantial, a larger sample size will presumably be able to confirm statistically significant differences between the cities with and without greenbelt for each year. According to a power analysis, the minimum sample size needed for an 80 % chance of detection of tests for *WSPC* values in 2006 and 2015 (with effect sizes of -0.55 and -0.64 standard deviation units, respectively) and adjusted *WUP* values in 2006 and 2015 (with effect sizes of -0.29 and -0.41 standard deviation units), would be 54, 39, 187, and 97 cities in each group, respectively, assuming the sample distribution would be reasonably normal (these sample sizes were estimated by calculating the effect sizes and applying a power test using these effect sizes, a significance level of 5 %, and a power of 80 %, for a two-sample *t*-test). Since reaching such a sample size of cities with greenbelts may be challenging within Europe, addressing the question irrefutably might be difficult at this time.

While the numbers of cities in each population-size category were much lower (between 8 and 12), the cities of medium size displayed significant differences between the average sprawl values of the two groups of cities for both years, mainly as a response to substantial differences between the average *LUP* values. Insignificant results for the medium-large city category, however, appear to be due to small sample size.

In contrast, the large and very large cities exhibited higher average values of sprawl in the cities with greenbelts. However, the differences in the average values of *WSPC* and adjusted *WUP* between the two groups were lower in 2015 (difference of 272.7 UPU/(inh. or job) in 2006 compared to 132.7 UPU/(inh. or job) in 2015 for *WSPC*, and 1.06 UPU/m² in 2006 compared to 0.54 in 2015 UPU/m² for adjusted *WUP*), showing that the decreases in the cities with greenbelts were much stronger. Using the annual linear rate of decrease, we envisioned that if the current trends continue, the group of large and very large cities will evince lower *WSPC* and adjusted *WUP* values in the cities with greenbelts than those without greenbelt as of 2024 and 2025, respectively, similar to the other population-size categories. With the same reasoning, it is likely that the cities in this category will demonstrate lower *LUP* values in cities with greenbelts than the ones without as of 2031. A similar result would manifest for the adjusted *PBA*, regardless of population size, in nearly four decades, when the percentage of built-up areas in the cities without greenbelt will exceed that of the cities with greenbelts, opposite to the current situation.

4.3. Comparison with other studies

Siedentop et al. (2016) analyzed greenbelts in Germany's regional plans in the four regions of Dusseldorf, Hanover, Mittelhessen, and Stuttgart, considering the "tightness" of greenbelts and their impacts on urban growth. The results suggested that greenbelts were effective at controlling urban growth at the regional scale. Dusseldorf, Hanover, and Stuttgart also were among the seven cities with greenbelts that we included from Germany, in which sprawl decreased. Our findings were consistent with their results in terms of the effectiveness of greenbelts, suggesting they are promising means of urban growth management in Germany at both regional and city scales.

A similar study analyzed urban sprawl in three cities with greenbelts (Frankfurt, London, and Seoul) between 1975 and 2015, using the *WUP* metric (Xie et al. 2020). Their results showed that urban sprawl decreased in the inner-cities of Frankfurt and London, i.e., in the areas surrounded by the greenbelt. However, sprawl increased in the outer areas of the cities, i.e., within a 40-km buffer beyond the greenbelt boundary. In Seoul, *WUP* increased inside as well as outside of the greenbelt, but the outside increase was exorbitant. The study provided evidence of leapfrogging development beyond the greenbelts and concluded that the greenbelts failed to control urban sprawl in these specific cases.

Comparing 30 cities with and 30 without greenbelt and applying the same method (*WUP*), our study does not support the debate of leapfrogging development at the city scale (i.e., within the city boundaries), in contrast to Xie et al. (2020). Xie et al. (2020) considered a very large buffer for each of the cities, which extended far beyond the official administrative city boundaries. The buffers included substantial parts of the territory of the independent neighboring cities, each of which has its own status and level of sprawl (e.g., Darmstadt in the outer area of Frankfurt, Oxford at a significant distance from London, and Incheon in the vicinity of Seoul). Hence, the levels of sprawl in the outer areas (encompassing neighboring regions) do not signify sprawl at the city level. Expecting that Frankfurt's greenbelt would control sprawl in Darmstadt is unreasonable, as those areas would clearly need to be controlled by additional measures to be taken by the neighboring regions.

We have taken into account in our calculations a buffer of 2 km (horizon of perception, *HP*; Jaeger et al., 2010b) around the city boundaries, which considers the greenbelt (and potential development in it) and the area beyond the city boundaries. In other words, leapfrogging development is examined to some degree while keeping the analysis at the city scale. However, since any leapfrogging development beyond the city boundaries is more of a regional concept, using a 2-km buffer may not catch it fully. Our study was not designed for an analysis of leapfrogging development beyond this 2-km buffer around the city boundaries. To address this issue, case-specific larger reporting units can be considered.

Some studies carried out in other contexts also support the effectiveness of greenbelts. Daniels (2010) investigated six American metropolitan counties with greenbelts in a 20-year timeframe and concluded that they were successful in land containment since the proportion of farmland preserved was larger than the amount of farmland converted to other types of landuse. However, due to the abundance of local governments and their low planning capacities, application of greenbelt policies is not common in the United States.

In contrast, Nazarnia et al. (2016a) compared Montreal, Quebec City, and Zurich metropolitan areas, none of which have a greenbelt. The study found that urban sprawl increased in all three cases between 1951 and 2011, but the increase was considerably lower in Zurich than in Montreal and Quebec City due to a much stronger public transportation system and more rigorous planning regulations since 1979. Hence, to mitigate urban sprawl in Montreal and Quebec City, the authors suggested a reduction in *LUP* and an expansion of public transport. Greenbelts help densification and can be applied in Montreal, Quebec City, and Zurich as a means for reducing *LUP* and mitigating urban sprawl.

Other types of urban growth strategies include urban growth boundaries (UGBs) and urban service boundaries (Bengston et al., 2004; Pendall et al., 2002). While a greenbelt designates a physical area, UGBs delineate lines to allocate separate zones to urban and rural areas (Gennaio et al., 2009). Urban service boundaries determine the extent to which infrastructure and public services will be provided. Hence, development beyond the corresponding boundary will be restricted (Bengston et al., 2004). Examining four Swiss municipalities, Gennaio et al. (2009) suggested that while the extent of developed land slightly expanded between 1970 and 2000, UGBs kept >70 % of the

development within the designated building zones, leading to lower LUP. Further quantitative and qualitative research is required to provide better understanding of the similarities, differences, and effectiveness of UGBs and urban service boundaries, compared to greenbelts.

4.4. Strengths, limitations, and future research suggestions

To the best of our knowledge, this is the first study that assesses the effectiveness of greenbelts at mitigating urban sprawl by comparing a considerable sample of cities with and without greenbelt and of a wide range of population sizes. Applying a novel method of adjustment to the boundaries of the cities helped compare the cities more accurately and fairly for each year. Our study used a suitable method for the measurement of urban sprawl that meets the 13 suitability criteria proposed by (Jaeger et al., 2010a). In contrast, the entropy method, while it has been used more frequently, is not a suitable measure of urban sprawl (Nazarnia et al., 2019) and should therefore be retired.

Some aspects could be improved in the future. While the cities were selected following a logical rationale according to population size and country, a future study could try to apply a more rigorous stratified sampling procedure. To enhance the likelihood of achieving statistically significant results for the comparison of cities with and without greenbelt for particular points in time, a future study could use a larger sample size and include cities from other continents. It would also be beneficial to consider various characteristics of greenbelts such as their age (year of implementation), spatial attributes (e.g., permeable or impermeable), area (relative to city size), degree of closedness, comparison of coastal cities with landlocked cities, and other properties (e.g., regulations, public transport systems, etc.) to analyze the effectiveness of greenbelts in more detail.

The definitions of greenbelts used by different countries may differ to some degree (App. A). Therefore, the exact criteria of a “greenbelt” are not always clear (Macdonald et al., 2021) which can cause confusion. For example, the greenbelt of the city of Münster is called a “green ring” rather than a “greenbelt”, but it clearly matches the definition of greenbelts used in this paper (App. K).

The effectiveness of other growth management strategies should be tested as well (Hersperger et al., 2017) using a similar approach as presented here. According to Hersperger et al. (2020), the most commonly used growth management approaches based on classifications by Bengston et al. (2004) and Rudolf et al. (2018) include public acquisition, regulation (planning-based), quality-oriented measures, incentives (market-based), and social learning (information-based). While greenbelts are one of the most momentous instruments of the regulation approach (planning-based), several other approaches and instruments are available that can also be effective in land preservation and in mitigating urban sprawl if correctly implemented. It would be helpful to examine the reasons of why some cities without greenbelt appeared less sprawled through time and to discover what planning regulations and policies or other measures were in effect during the studied period that have reversed the sprawl trend.

5. Conclusions and recommendations

Multiple growth management strategies have been proposed to control sprawl, including the greenbelt policy that dates back to the 1930s. However, the extent of the effectiveness of greenbelts has been subject to controversy. This study found that (1) greenbelts have been substantially effective in controlling urban sprawl and have led to decreases in sprawl in 90 % of the cities in which they were put in place. (2) In cities in which urban sprawl was reduced over time, the relative decreases were much stronger in cities with greenbelts. (3) Greenbelts were somewhat more effective in cities in which population size was greater. (4) The most important effect was a substantial reduction in LUP as a result of densification of built-up areas.

Accordingly, we recommend the use of greenbelts as an essential part

of any de-sprawling strategy (Hennig et al., 2015) toward more compact green cities (Artmann et al., 2019), where applicable. Municipalities in the surrounding areas need to be supportive of limiting urban sprawl as well to void the issue of leapfrogging. They need to refrain from undermining the positive effects of greenbelts in neighboring cities. Artmann et al. (2019) integrated the concepts of “smart growth” and “green infrastructure” and developed a conceptual framework for “smart-compact-green cities” to address the danger of losing green spaces in compact cities as a result of in-filling. Greenbelts not only help achieve more compact forms of urban development, they also supply an essential share of ecosystem services in urbanized areas.

In cities in which a greenbelt is not feasible due to the existing spatial arrangement of built-up areas, the use of greenways or green wedges as urban development boundaries is advised, as done in the case of Leipzig. We observed strong decreases in a few cities without greenbelt, which were due to specific regulations, policies, or other measures in effect during the time period studied. As an example, the Grüne Ring Leipzig (Green Ring Leipzig - GRL) was founded in 1996 as a “voluntary and equal working group” by >20 municipalities to jointly improve the attractiveness of the region. This inter-municipal association has worked out a locational advantage over other regions (Grüner Ring Leipzig, n. d.). Antwerp and Lincoln, similarly, demonstrated notable decreases in LUP, i.e., housing more people and employees.

At the local level, growth management policies are more often applied in municipalities of larger sizes because of their higher planning capacity, while smaller municipalities may be less capable due to limited financial and administrative resources (Rudolf et al., 2018). It is crucial to consider the context of the target locations as well, such as their social, political, economic, and geographical situation, and their capacities in implementing certain strategies, e.g., their transformative capacity (Wolfram et al., 2019).

Identifying case-specific drivers of urban sprawl would also help propose additional measures for each city. Densification should be practiced more rigorously, especially within the existing built-up areas, to mitigate sprawl and its negative impacts.

Declaration of Competing Interest

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

Acknowledgements

We are very grateful to Angela Kross, Mehrdokht Pourali, Nick Revington, Ulrich Schumacher, and Craig Townsend for their helpful feedback and suggestions throughout this study, as well as to two reviewers for their constructive comments which helped improve our manuscript. We thank the City of Münster, Germany, for their permission to reproduce their map of Münster’s green ring in App. K. We would also like to express our sincere appreciation to Mojgan Koohi and Abbas Pourtaherian for their endless support.

Appendices A–K. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.landurbplan.2022.104532>.

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