How do greenbelts affect urban sprawl in European cities?

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ABSTRACT

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As Europe takes continuous steps towards urbanization, many cities in this continent suffer from the negative repercussions caused by urban sprawl. Among the efforts adopted to overcome urban sprawl and its adverse impacts is the greenbelt policy that is highly popular in several European countries. However, the actual effectiveness of this growth management strategy was to be determined. Using a sample of 60 European cities, 30 of which have greenbelts, this study compares (1) changes in urban sprawl in a 9-year timeframe (2006-2015) between the cities with and without greenbelts, and (2) the level of sprawl between the cities with and without greenbelts 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 showed that (1) greenbelts have been largely effective as an urban growth management strategy in slowing down urban sprawl; and in most cases, they also have helped reduce sprawl, (2) While urban sprawl decreased also in some cities without greenbelts, the relative decrease in urban 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 can be employed as an important part of any de-sprawling strategies in future urban and regional planning, environmental monitoring, and formulating new scenarios as well as targets and limits to urban sprawl in support of more sustainable forms of urban development.

Keywords: Built-up area, Dispersion, Europe, Growth management strategies, Land uptake, Monitoring, Urban development, Urban growth, Utilization density, Weighted Urban Proliferation (*WUP*), Weighted Sprawl per Capita (*WSPC*)

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Contribution of Authors

As first author, I was responsible for conception, data collection, data corrections, quantitative calculations, data analysis, interpretation of data and results, and the writing of the manuscript. The manuscript was co-authored by Dr. Jochen Jaeger, who advised on experimental design, data analysis and statistics, editing, and overall revisions to the manuscript.

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To my beloved parents, Mojgan and Abbas, for their faith.

In loving memory of those we lost on flight PS752…

1. Introduction

The fast and largely uncontrolled expansion of urban areas across the planet is subject to controversy regarding its detrimental consequences. Urban sprawl generally refers to dispersed, low-density development on undeveloped land, which is currently following an unsustainable trend, and it includes various negative impacts, particularly many significant environmental consequences (European Environment Agency & Swiss Federal Office for the Environment, 2016). The United Nations have claimed that Europe is among the most urbanized geographic regions in the world with 74 percent of the population living in urban areas in 2018 (United Nations, 2019); and Hennig et al. (2015) have shown in their multi-scale analysis that an extensive part of Europe is affected by urban sprawl.

In some countries, one of the policies to prevent urban sprawl and to stop the permeation of built-up areas into the landscape is the use of greenbelts around the cities or regions (Baing, 2010; Hack, 2012; A. T. Han, 2019; Kovács et al., 2019). A greenbelt is an enduring open space such as a forest or farmland drawn around a city or a region. Its main purpose is to restrict urban growth and restrain urban sprawl (Bengston & Youn, 2006). Greenbelts were applied for the first time around London (H. Han & Xu, 2017) in the 1930s (Amati & Yokohari, 2007), and they have been considered as successful planning tools in the UK ever since (Kovács et al., 2019). They quickly became a global means for potentially controlling urban expansion (Hack, 2012), and multiple countries, specifically in Europe, tried to take advantage of this emerging policy (A. T. Han, 2019). One example of these countries is Germany, which has claimed that its greenbelts have controlled urban sprawl more effectively than other planning tools (Baing, 2010). However, some authors have argued that this strategy does not limit urban sprawl in every situation, and in some cases, it acts oppositely (Anas et al., 1998; A. T. Han, 2019). This study aims at analyzing urban sprawl among multiple European cities with and without greenbelts, with different population sizes, to provide a comprehensive view on the functionality of greenbelts.

Most of the existing literature in this context 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 condition of urban sprawl in a few specific areas (e.g., Xie et al., 2020). Moreover, there has been relatively low interest in studying urban issues at the European level (Kasanko et al., 2006), which makes it worthwhile to focus on cities in this area. Kasanko et al. (2006) considered three probable explanations for the low interest in carrying out urban studies on European cities: (1) European cities are usually considered "too stable" and consequently not stimulating as the focus of the research, (2) The urban policy is weak at the European level regarding the "relatively low visibility of urban issues", and (3) It is difficult to obtain comparable data at the scale of the cities in Europe.

In order to articulate research question and hypotheses, it is important to consider the existing literature about greenbelts and urban sprawl as well as their relationship with population size as an important factor to take into account. However, since no studies were found that examine the relationship between population size and greenbelts, I employed my personal knowledge and general background in urban planning to generate hypotheses in this regard.

According to Duranton and Puga (2014), the main drivers of population growth of cities in developed economies include "transportation and housing supply", "amenities", "agglomeration effects, in particular, those related to human capital and entrepreneurship", and "technology and shocks to specific cities or industries". Since these drivers are generally stronger in more developed cities, mainly with larger population sizes, it is fair to conclude that the cities of greater populations would most likely have higher absolute population growth (but not necessarily higher relative population growth). Population growth as a potential factor contributing to urban sprawl would consequently make cities with larger populations more susceptible to this phenomenon, increasing the necessity of implementing restrictive policies including greenbelts. Hence, applying greenbelts and limiting the widespread construction in cities with larger population sizes would lead to greater densification of the existing built-up areas. Having said that, it is anticipated that the greenbelts as the means of controlling urban sprawl would have a stronger influence on cities with larger population sizes.

Regarding the opposing arguments about the effectiveness of greenbelts, this research seeks to address the following overall question:

How do greenbelts affect urban sprawl in European cities with different population sizes?

The hypotheses that will be tested by this research include:

1) The European cities having put greenbelts in place are generally less sprawled than cities without greenbelts.
2) Urban sprawl has increased more slowly in the European cities that have greenbelts than in those without greenbelts.
3) Greenbelts are more effective in controlling 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 greenbelts will be more pronounced.

The findings of such a study can be useful for environmental monitoring and for future urban and regional planning, as well as for generating new scenarios and setting targets and limits in support of more sustainable urban development. Also, the results can help evaluate if additional measures are needed to stop urban sprawl.

2. Literature Review

`To understand the significance of this research, the review of the literature introduces greenbelts, covers different definitions assigned to urban sprawl, and explores its causes and consequences. Moreover, a discussion of different methods that have been used to quantify the degree of urban sprawl is presented, and the important criteria by which the suitability of the methods can be evaluated are introduced. Figure 1 presents a general overview of the topics covered in the literature review and indicates the connections among different sections.

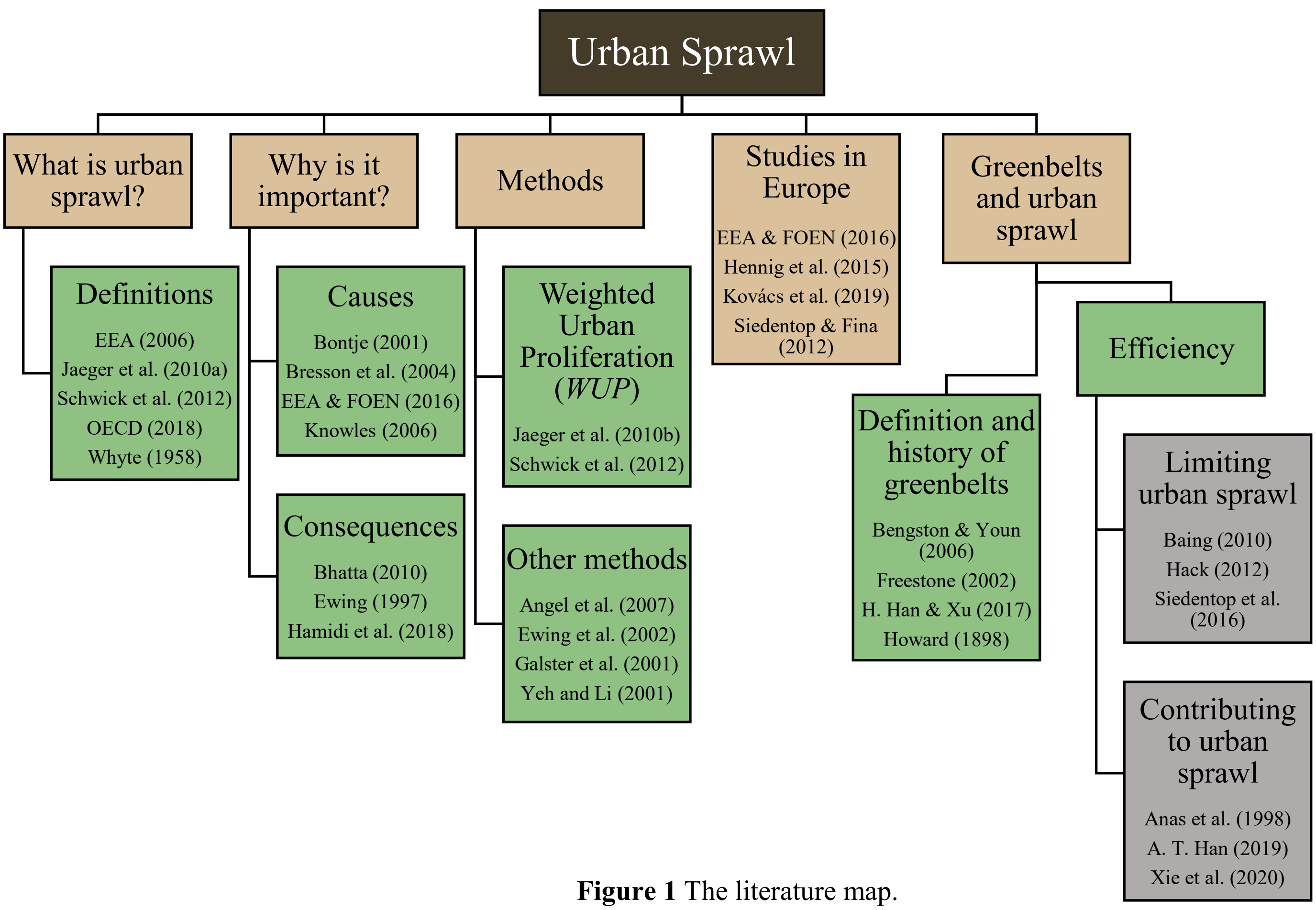

Figure 1 The literature map.

2.1 Definitions of urban sprawl

The first use of the term “urban sprawl” was in 1958 in the Fortune magazine by William Whyte (Whyte, 1958). In German literature, the word “Zersiedelung” had appeared even earlier in the 1920s with the same interpretation of this phenomenon and was increasingly used in German-speaking countries after World War II (Akademie für Raumforschung und Landesplanung, 1970).

Various definitions of urban sprawl have been proposed by many scholars ever since, but no agreement has been made on the main components that define it. One of the reasons is that the term urban sprawl is used in different fields of study and defined from different points of view (Maier et al., 2006). Moreover, it is sometimes confused with similar phenomena such as “suburbanization”, “suburban development”, and “urban growth” (Maier et al., 2006), while “urban growth”, for example, refers to the development of urban areas regardless of their spatial arrangement and utilization density (EEA & FOEN, 2016), which can lead to urban sprawl. But most importantly, this confusion is caused by the definitions that attempt to define urban sprawl using its causes and consequences and integrate them with the main concept (Jaeger et al., 2010a). In other words, these definitions mainly focus on “describing” urban sprawl rather than “defining” it (Bhatta et al., 2010).

Table 1 presents an overview of the most common definitions of urban sprawl. Reviewing different definitions is not only important for distinguishing varied perspectives regarding urban sprawl, but also essential for evaluating different methods of measurement.

Table 1 Definitions of urban sprawl.

Definition	Source
Sprawl is identified as the combination of three characteristics. "(1) leapfrog or scattered development; (2) commercial strip development; and (3) large expanses of low-density or single-use developments—as well as by such indicators as low accessibility and lack of functional open space".	Ewing (1997, p. 108)
Sprawl is "low-density, automobile-dependent development beyond the edge of service and employment areas".	Sierra Club (1998, para. 5)
Sprawl is counted as "any extension of the suburban margin, the spread of development onto sensitive greenfields and agricultural soils, increases in highway congestion, the proliferation of new subdivisions of homogeneous and low density, single-family housing".	Bourne (2001, p. 26)
Sprawl is conceptually explained "based on eight distinct dimensions of land use patterns: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity. Sprawl is defined as a condition of land use that is represented by low values on one or more of these dimensions".	Galster et al. (2001, p. 1)
Sprawl is "the process in which the spread of development across the landscape far outpaces population growth. The landscape sprawl creates has four dimensions: a population that is widely dispersed in low-density development; rigidly separated homes, shops, and workplaces; a network of roads marked by huge blocks and poor access; and a lack of well-defined, thriving activity centers, such as downtowns and town centers. Most of the other features usually associated with sprawl – the lack of transportation choices, relative uniformity of housing options or the difficulty of walking – are a result of these conditions".	Ewing et al. (2002, p. 3)
Sprawl is "a process of large-scale real estate development resulting in low-density, scattered, discontinuous car-dependent construction, usually on the periphery of declining older suburbs and shrinking city centers".	Hayden, 2004 (p. 8)
Sprawl is "the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas".	European Environment Agency & European Commission (2006, p. 6)
"Urban sprawl is characterized by unplanned and uneven pattern of growth, driven by multitude of processes and leading to inefficient resource utilization".	Sudhira & Ramachandra (2007, p. 2)
"Urban sprawl is visually perceptible. A landscape suffers from urban sprawl if it is permeated by urban development or solitary buildings. For a given total amount of build-up area, the degree of urban sprawl will depend on how strongly clumped or dispersed the patches of urban area and buildings are; the lowest degree of sprawl corresponds to the situation when all urban area is clumped together into the shape of a circle. The highest possible degree of sprawl is assumed in an area that is completely built over. Therefore, the more urban area present in a landscape and the more dispersed the urban patches, the higher the degree of urban sprawl".	Jaeger et al. (2010a, p. 400)

Table 1 Continued

Definition	Source
"Urban sprawl is a phenomenon that can be visually perceived in the landscape. The more heavily permeated a landscape by buildings, the more sprawled the landscape. Urban sprawl therefore denotes the extent of the area that is built-up and its dispersion in the landscape in relation to the utilization of built-up land for living and work. The more area built over and the more dispersed the buildings, and the less the utilization, the higher the degree of urban sprawl".	Schwick et al. (2012, p. 115)
"The term urban sprawl refers to the uncontrolled spread of towns and villages into undeveloped areas".	Swiss Federal Office for the Environment (2017, para. 1)
Urban sprawl is "an urban development pattern characterised by low population density that can be manifested in multiple ways. That is, an urban area may be sprawled because the population density is, on average, low. Furthermore, urban areas characterised by high average density can be considered sprawled if density varies widely across their footprint, leaving a substantial portion of urban land exposed to very low density levels. Urban sprawl can also be manifested in development that is discontinuous, strongly scattered and decentralised, where a large number of unconnected fragments are separated by large parts of non-artificial surfaces."	OECD (2018, p. 29)

One of the best definitions that differentiates the causes and consequences of urban sprawl from the main phenomenon is the one proposed by Schwick et al. (2012). This definition is derived from the one initially proposed by Jaeger et al. (2010a) and has added population density to the dimensions of urban sprawl as an important component (Fig. 2).

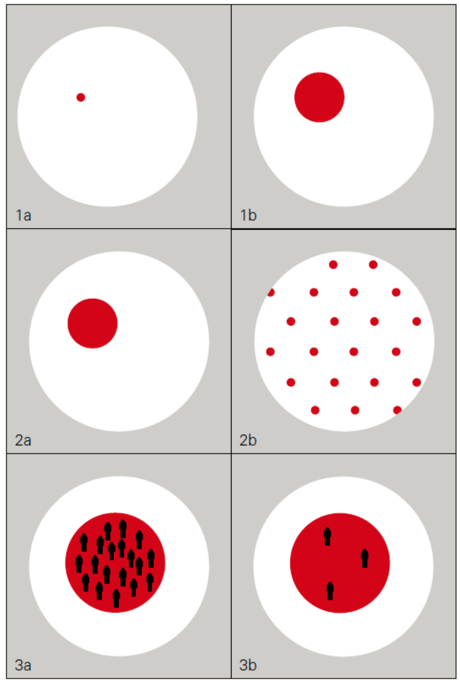

Figure 2 Three dimensions of sprawl. Urban sprawl is higher when 1) the built-up areas (red) in a landscape (white) increase, 2) the built-up areas become more dispersed, and 3) the utilization density becomes lower (i.e. the uptake of built-up area per inhabitant or job becomes higher) (Schwick et al., 2012, p. 117).

2.2 Drivers of urban sprawl

Various factors contribute to what we know as urban sprawl today. According to the joint report of EEA and FOEN (2016), "Urban Sprawl in Europe", a sequence of most important drivers of urban sprawl, derived from classifications by Hersperger and Bürgi (2009), Christiansen and Loftsgarden (2011), and Habibi and Asadi (2011), are as follows:

2.2.1 Demographic drivers

The size and demographic structure of the population is an influential factor for the proportion of built-up areas. If all the other factors are equal, clearly more space is needed for accommodating a larger population (EEA & FOEN, 2016). Accordingly, migration has an effect on urban sprawl in different regions since it contributes to the changes in the population size (Bontje, 2001). In addition, the desire of living in single-family houses results in people moving from city centers to more favorable areas. This occurrence is more evident in regions whose population is mostly formed by elderly people (EEA & FOEN, 2016).

2.2.2 Socio-economic drivers

The social advertisements in societies promoting higher consumption levels impose the lifestyles demanding single-family houses and personal automobiles (EEA & FOEN, 2016). Accordingly, the resulting increase of the gross domestic product (GDP) is often associated with the increase in urban sprawl (Bresson et al., 2004). However, car ownership and GDP as separate factors are so closely related to urban sprawl that it is often hard to distinguish which one is the cause or the effect of the other one (EEA & FOEN, 2016; Torres et al., 2016).

2.2.3 Political drivers

Politics has a significant role in preventing or promoting urban sprawl by applying specific regulations, planning frameworks, subsidies, and taxes (EEA & FOEN, 2016). As an example, subsidies allocated to purchasing automobiles contribute to urban sprawl (Su & DeSalvo, 2008), while constraints regarding the expansion of designated building zones lead to an increase in the density of the existing built-up areas and consequently, control the extent of urban sprawl (Bertaud & Brueckner, 2005).

2.2.4 Technological drivers

After industrialization in the 20th century, the need for workforce by large factories emerged, that induced people to migrate from where they lived to urban areas (EEA & FOEN, 2016). Later, the possibility of commuting by personal cars eliminated the necessity of living close to the workplaces (Knowles, 2006). This occasion as well as high costs of residing in urban cores encouraged people to move to the suburbs and resulted in the creation of more dispersed urban areas (Anas et al., 1998). Today, as technological developments continue, working remotely is feasible as well (Hardill & Green, 2003), which can contribute to further dispersion and consequently, increased sprawl (EEA & FOEN, 2016).

2.2.5 Geophysical conditions

The geophysical situation is one of the prominent factors that contribute to the pattern of development of built-up areas in a given land. The lands which are not physically suitable for building, known as "irreclaimable areas", limit the possibility of construction and therefore, prevent further urban sprawl (EEA & FOEN, 2016). On the contrary, valleys and lowlands that are mostly allocated to agriculture are likely to be used as construction zones, if they are situated in the proximity of urban areas, since they are inexpensive and are more exposed to the transformation pressure (Mann, 2009).

2.3 Consequences of urban sprawl

Consequences of urban sprawl include both negative and positive effects according to the literature. Some of the positive impacts, stated by (Bhatta, 2010), include the extension of more efficient fundamental services such as transportation, improvement of the quality of life resulting from better and more frequent opportunities, improved educational and health care facilities, and greater economic production.

Negative impacts, however, have always outweighed positive ones. Understanding the negative effects of urban sprawl on different facets of life is essential for taking steps against this phenomenon and controlling the permeation of urban characteristics into the unspoiled landscape.

According to the literature, the most important consequences of urban sprawl are collected in four categories:

2.3.1 Environmental impacts

Urban sprawl causes energy inefficiencies. While automobiles consume more fuel in places with higher densities due to traffic congestion, the consumption of fuel is remarkably less in dense areas since the vehicles commute shorter distances (Newman & Kenworthy, 1988). Consequently, the car-dependent lifestyle imposed by greater distances leads to more greenhouse gas emissions and a higher contribution to both climate warming and air pollution (Stoel, 1999). Another example is electricity. In addition to the higher expenditures associated with the extension of the delivery system and its maintenance, distributing electricity over farther distances results in more power loss (Bhatta, 2010).

Another form of environmental impact is the disruption of ecosystems and habitat fragmentation by seizing open spaces, forests, and farmlands. Urban development requirements including roads and pipelines permeate natural landscapes, break up the wildlife habitat, lead to changes in the patterns of animal movements, and result in the loss of wildlife populations (Bhatta, 2010).

2.3.2 Economic impacts

While some scholars have listed several positive impacts of urban sprawl on the economy including higher economic production (Bhatta, 2010), negative implications of this phenomenon are considerably more and serious. Higher costs of extending and maintaining infrastructure and public services are substantial. In places with dispersed built-up areas and longer distances, providing infrastructure and services including public transport, roads, electricity, water, etc. is strikingly costly and requires greater investments (Ewing, 1997).

2.3.3 Social impacts

To highlight the importance of social consequences associated with urban sprawl, Ewing (1997, p. 117) stated that "these costs are intangible, to be sure, but they are as real as travel costs and wetland losses". Different social impacts have been assigned to urban sprawl in the literature. Two main types of these impacts have been identified as "deprivation of access" and "environmental deprivation" (Popenoe, 1979, as cited in Ewing, 1997).

"Deprivation of access" refers to having limited access to services, facilities and even job positions due to the restrictions imposed by car-dependency, which is most evident for the poor population, young children, and the elderly. On the other hand, environmental deprivation implies "the absence of elements that provide activity and stimulation" (Popenoe, 1979, as cited in Ewing, 1997, p. 117). The lack of variety in the physical forms of sprawled areas as well as shortage of social interaction leads to environmental deprivation (Ewing, 1997).

2.3.4 Impacts on public health

One of the most controversial consequences of urban sprawl is its direct and indirect effects on public health. The recent study by Hamidi et al. (2018) has proven that urban sprawl has a significant negative relationship with life expectancy. Cities with dense built-up areas have remarkably higher life expectancy than sprawled areas. Factors including lack of proper accessibility to health centers, longer commuting durations in urgent situations, and lower availability of healthy food directly contribute to mortality rates; And factors such as distance traveled, which is related to density and can lead to traffic casualties, have indirect effects (Hamidi et al., 2018).

2.4 Methods used for measuring urban sprawl

In this section, a brief overview of the most common methods for the measurement of urban sprawl is given.

- Yeh and Li (2001) introduced Shannon's Entropy as a method for measuring urban sprawl.

They claimed that this method can be used to quantify how spatially concentrated or dispersed urban areas are among *n* zones or wards. The zones are defined using remote sensing data and GIS, and the value of Shannon's Entropy is calculated by the following equation:

$$H_n = \sum_{i}^{n} p_i \log {}^{1}/_{p_i} \quad ,$$

where p_i is the proportion of urban areas in the *i*th zone.

Moreover, since the Entropy depends on the size of the zones, by parting the zones to smaller areas, the value of the Entropy and consequently urban sprawl increases:

$$H_n = \sum_{i=1}^{m} p_i \log\left({}^{1}/_{p_i}\right) + \sum_{j=1}^{m}\left[p_i \sum_{\mathrm{i}=1}^{n_j}\left({}^{p_{i(i)}}/_{p_i}\right)\log\left({}^{p_i}/_{p_{i(j)}}\right)\right]$$

In this equation, *j* presents the *j*th zone at the region scale, the total number of zones at the region scale is displayed by *m*, and p_j is the proportion of urban areas in the *j*th zone at the region scale.

A recent study by Nazarnia et al. (2019) examined this method regarding the 13 suitability criteria for measuring urban sprawl introduced by Jaeger et al. (2010a). "The 13 criteria include

(1) intuitive interpretation, (2) mathematical simplicity, (3) modest data requirements, (4) low sensitivity to very small patches of urban area, (5) monotonous response to increases in urban area, (6) monotonous response to increasing distance between two urban patches when within the scale of analysis, (7) monotonous response to increased spreading of three urban patches, (8) same direction of the metric's responses to the processes in criteria 5, 6 and 7, (9) continuous response to the merging of two urban patches, (10) independence of the metric from the location of the pattern of urban patches within the reporting unit, (11) continuous response to increasing distance between two urban patches when they move beyond the scale of analysis, (12) mathematical homogeneity (i.e., intensive or extensive measure) and (13) additivity (i.e., additive or area-proportionately additive measure)" (Jaeger et al., 2010a, p. 397).

The study proved that Entropy meets only 5 criteria and is not a suitable metric for measuring the degree of urban sprawl.

- Galster et al. (2001) defined urban sprawl with eight different indicators of land use pattern including density, concentration, clustering, centrality, nuclearity, proximity, continuity, and mixed uses[1]. The first six dimensions were used to measure urban sprawl in 13 different American urbanized areas, and low values of one or more of these indices represented sprawl in the intended locations. In this study, however, the degree of urban sprawl is not measurable independently.

[1] Density: "The average number of residential units or employees per square mile in a UA (urbanized areas)".
Concentration: "The degree to which housing units or jobs are disproportionately located or spread evenly in the UA".
Clustering: "The degree to which development within any one-mile-square area is clustered within one of the four one-half-mile squares contained within (as opposed to spread evenly throughout)".
Centrality: "The degree to which observations of a given land use are located near the CBD of a UA".
Nuclearity: "The extent to which a UA is characterized by a mononuclear pattern of development".
Proximity: "The degree to which different land uses are close to each other across a UA".
Continuity: "The degree to which developable land has been developed in an unbroken fashion throughout the UA".
Mixed uses: "The degree to which substantial numbers of two different land uses (e.g., housing units and employees) exist within the same area and this pattern is typical throughout the UA" (Galster et al., 2001, p. 700-703).

- Ewing et al. (2002) proposed the "Four Factor Sprawl Index" indicate to the level of urban sprawl and used it to measure this phenomenon in 83 American metropolitan areas. This index is compounded by four measurable factors including (1) Residential density; (2) neighborhood mix of homes, jobs, and services; (3) strength of activity centers and downtowns, and (4) accessibility of the street network. Each of the aforesaid factors is made up of multiple indicators, 22 in total, and the value of the ultimate Four Factor Sprawl Index is procured by combining the values of factors. In this method, the abundance of indices for calculating the Four Factor Sprawl Index is a genuine difficulty.

- Angel et al. (2007) used five metrics to define and measure what they presented as "key manifestations of sprawl". These metrics comprise main urban core, secondary urban core, urban fringe, ribbon development, and scatter development and were applied to two cities, Bangkok and Minneapolis. Using this method, the geographic patterns and changes in the cities were tracked in time. This method is appropriate for making comparisons between cities or different time slices regarding the five facets of sprawl. However, urban sprawl itself is not measured independently using a single coherent metric.

- Jaeger et al. (2010b) introduced four new metrics including the degree of urban dispersion (*DIS*), total sprawl (*TS*), degree of urban permeation of the landscape (*UP*), and sprawl per capita (*SPC*) for the measurement of urban sprawl. In this method, urban sprawl is portrayed from a geometric perspective, and the metrics are calculated using the following equations:

$$DIS = \frac{1}{A_{\text{built-up}}} \cdot \int_{\vec{x} \in \text{built-up}} \frac{1}{\int_{\substack{\vec{x} \in \text{built-up} \\ \text{and } |\vec{x}-\vec{y}|<HP}} d\vec{y}} \int_{\substack{\vec{y} \in \text{built-up} \\ \text{and } |\vec{x}-\vec{y}|<HP}} \sqrt{\frac{2 \cdot |\vec{x}-\vec{y}|}{1\text{ m}}} + 1 - 1 \, d\vec{y} \, d\vec{x} \quad ,$$

$$TS = DIS \times \text{urban area} \quad ,$$

$$UP = {}^{TS}/_{\text{size of the landscape studied}} \quad ,$$

$$SPC = {}^{TS}/_{\text{number of inhabitants}} \quad .$$

- Siedentop and Fina (2012) used 8 indicators to provide a comparative evaluation of urban landuse change among 26 European countries. The indicators are collected in three categories of composition, pattern, and density; and they include land consumption, normalized urban land consumption, growth of urban land, sealing degree of urban land, effective open space, decline of effective open space, Gini index, and urban density. In this study, however, the degree of urban sprawl is not measurable independently.

- Schwick et al. (2012) proposed the Weighted Urban Proliferation (*WUP*) method, which is derived from the method developed by Jaeger et al. (2010b) and integrates three main components in one metric. These components are the percentage of built-up area (*PBA*), the dispersion of built-up areas (*DIS*), and land uptake per person (*LUP*). This method is based on the understanding that the overall degree of urban sprawl is higher when the built-up areas in a landscape increase, the built-up areas become more dispersed, and uptake of built-up area per inhabitant or job is higher. The degree of urban sprawl in this method is calculated with the following equation:

$$WUP = (PBA \times DIS) \times w_1(DIS) \times w_2(LUP)$$

In this equation, dispersion and land uptake per person are weighted using two functions, $w_1(DIS)$ and $w_2(LUP)$, respectively. Values for $w_1(DIS)$ vary between 0.5 and 1.5, with lower values allocated to more compact built-up areas, highlighting the differences between compact and dispersed built-up areas more evidently. Likewise, values of $w_2(LUP)$ range from 0 to 1, with higher values assigned to greater land occupation by each individual, i.e. lower utilization density (*UD*) (Schwick et al., 2012).

Weighted Urban Proliferation is expressed in urban permeation units per m^2 of land (UPU/m^2) and has been used in several studies including measuring urban sprawl in Switzerland (Schwick et al., 2012), multiple European countries (EEA & FOEN, 2016; Hennig et al., 2015) as well as Montreal and Quebec City (Nazarnia et al., 2016a).

Following *WUP*, Weighted Sprawl Per Capita (*WSPC*) has been established, which is an intensive measure regarding the population rather than the area of the reporting unit, and it can be used on a per-capita basis. It indicates how much each person contributes to urban sprawl on average (Behnisch et al., subm.).

$$WSPC = {A_{\text{reporting unit}}}/{N_{\text{inh+job}}} \cdot WUP$$

2.5 Measurement of urban sprawl in Europe

Low interest in urban research at the European level has left us with very limited studies in this context. Among the few existing studies about urban sprawl in Europe, most have compared several areas qualitatively or measured various urban aspects separately rather than quantifying urban sprawl as a specific phenomenon. An example of such studies is the research by Kovács et al. (2019), which has compared the sprawl of four European functional urban areas with greenbelts based on their landscape conditions, spatial planning traditions, landscape protection, settlement hierarchy, etc. Among the studies that quantitatively measured urban sprawl is the one by Siedentop and Fina (2012) which suggested that Ireland, Portugal, and Spain have been the most sprawling European countries between 1990 and 2005 (Siedentop & Fina, 2012).

One remarkable quantitative study on urban sprawl in Europe is the one by Hennig et al. (2015), which used the *WUP* method to measure urban sprawl consistently across Europe at three scales according to the Nomenclature of Territorial Units of Statistics (NUTS). More detailed results of this study are provided in the joint report of EEA and FOEN (2016).

1. Sprawl at the country level (NUTS-0)

The study by Hennig et al. (2015) illustrated that a vast area in Europe is affected by urban sprawl. The average value for all of Europe (32 countries considered) in 2006 was calculated as 1.56 UPU/m^2 (Fig. 3). However, the values for each country differ greatly. Iceland (0.11 UPU/m^2) and Scandinavian countries have experienced the lowest degrees of urban sprawl, while the Benelux countries are the most sprawled countries within Europe (with 6.48 UPU/m^2 in Belgium). This is mainly due to much higher population densities in the Benelux countries and much lower population densities in the Scandinavian countries than the European average. Moreover, due to the remoteness of Scandinavian countries, there is not much traffic through them, where as there is a substantial amount of transit across the Benelux countries from other countries surrounding them (Hennig et al., 2015).

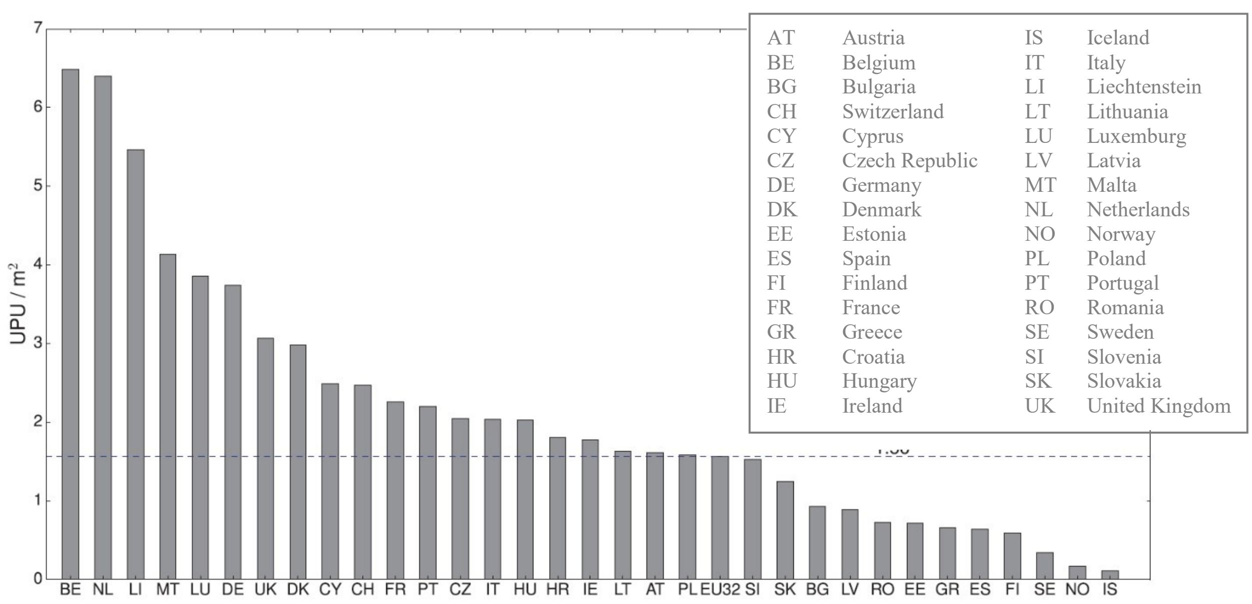

Figure 3 *WUP* values for each member of the European Union (EU) or the European Free Trade Association (EFTA) in 2006 (Hennig et al., 2015, p. 485).

2. Sprawl at the NUTS-2 level

The NUTS-2 level refers to the "basic regions for the application of regional policies" (Hennig et al., 2015, p. 484). At this scale, the highest values of sprawl were found in the industrialized regions adjacent to the urban cores and along the main transportation passages. Highly sprawled clusters at the NUTS-2 level were located in north-eastern France, Belgium, Netherlands, western Germany, and a large part of England (Fig. 4).

3. Sprawl at the 1-km^2 grid level

The 1-km^2 grid level is the finest scale considered in the multi-scale analysis by Hennig et al. (2015). The maps at this scale provide more visible patterns of transportation corridors, city centers, and coastlines where the highest values of sprawl are mostly found. An example of a highly sprawled area at this scale is Côte d'Azur (French Riviera) along the coast.

Figure 4 illustrates the degrees of urban sprawl in 2006 in NUTS-2 regions, while Figure 3 provides an overview of the *WUP* values in European countries in 2006.

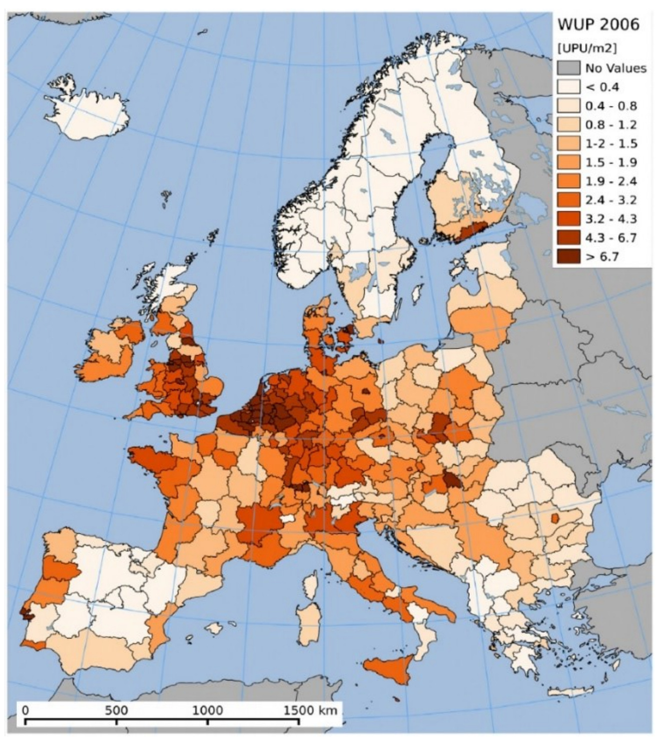

Figure 4 Map of *WUP* in NUTS-2 regions of Europe in 2006 (Hennig et al., 2015, p. 486).

2.6 Greenbelts: Definition, history, and efficacy

The term "greenbelt" refers to a physical perpetual open land such as a forest, farmland, or other types of greenspace, surrounding a city or a region, that is planned to restrict urban expansion, and development on it is illegal or rigidly regulated (Bengston & Youn, 2006). A greenbelt can be a narrow strip, or it can cover a broad area of the countryside (Freestone, 2002), and its extension is defined by the government (H. Han & Xu, 2017). The activities within this land are rigorously limited and aligned with the sustainability of the city or region (H. Han & Xu, 2017).

Freestone (2002, p. 67) stated: "To think of greenbelts is to think inescapably of Ebenezer Howard, British town and country planning, and the London Green Belt" pointing out to the fact that the greenbelt initiative originated from Ebenezer Howard's "Garden Cities" idea (Howard, 1898), and that the first implementation of this initiative dates back to the establishment of London greenbelt (Han & Xu, 2017) in the 1930s (Amati & Yokohari, 2007). Greenbelts were considered as an important spatial planning tool in the UK (Kovács et al., 2019), and gained considerable global popularity in the 20th century as a potential technique to limit urban growth (Hack, 2012). Regarding the importance of greenbelt strategy, Baing (2010) emphasized the effectiveness of centralized planning policy and the application of greenbelts that have been more beneficial in preventing urban sprawl in Germany than other German planning tools (Baing, 2010). By carrying out empirical research on four regions in Germany, Siedentop et al. (2016) have also suggested that greenbelts are effective in preserving landscapes. Canada, Australia, South Korea, and the United States are additional examples of countries that have incorporated greenbelt policy in their spatial planning system (A. T. Han, 2019).

The efficacy of greenbelts, however, is subject to controversy since there are shreds of evidence indicating that limiting development activities and confining lands can cause accelerated development inside the greenbelt itself or beyond the greenbelt ("leapfrogging" development), which both contribute to urban sprawl (A. T. Han, 2019). Moreover, while greenbelts may be considered as a means to improve the local environment by limiting development in the entire metropolitan area, they divert the urban growth, which causes environmental costs elsewhere (Anas et al., 1998). In this regard, a comparative study by Xie et al. (2020) has measured urban sprawl quantitatively and demonstrated that the designation of greenbelts in three metropolitan areas of Seoul, Frankfurt, and London has failed to curb urban sprawl at both scales of urban centers and of the wider region. On the other hand, this study points at some European cities such as Barcelona, Berlin, Cologne, Vienna, and Vitoria-Gasteiz as successful examples of cities adopting greenbelts. This claim, however, has not yet been tested quantitatively.

2.7 Outlook

Sustainable urban development as an optimum form of urban growth is of great importance considering the high rates of urbanization in today's world. Despite many arguments and studies about urban sprawl as a critical issue worldwide, no agreement has been reached on the ways it should be measured and controlled in order to avoid the succeeding adverse repercussions. Using greenbelts as a potential means to curb urban sprawl has been incorporated in the planning tools of some countries in recent decades. However, the efficacy of this policy has not been tested in comparison with cases without this feature, especially at the scale of cities and controlling for different characteristics such as population size. Thus, it is necessary to put more effort into this subject.

To evaluate the functionality of greenbelts, it is necessary to use a single coherent metric for quantifying urban sprawl, which meets the suitability criteria that are paramount for measures of this phenomenon. The new metrics of urban permeation and weighted urban proliferation (Jaeger et al., 2010b; Schwick et al., 2012) have proven to be reliable since they apply one measure to quantify the degree of urban sprawl, consider the spatial arrangement of built-up areas, and meet all 13 suitability criteria (Jaeger et al., 2010a). These characteristics distinguish this method from many other methods in the literature. Hence, in this study, the weighted urban proliferation method will be used for calculating the level of sprawl.

3. Paper manuscript: How do greenbelts affect urban sprawl in European cities?

3.1 Disputed effectiveness of greenbelts

Accelerated and unrestrained development of urban areas has always been a controversial issue due to many adverse consequences, especially in recent decades since WWII. Urban sprawl refers to dispersed, low-density development on undeveloped land, which is highly criticized globally because of current unsustainable trends and significant environmental repercussions (EEA & FOEN, 2016; OECD 2018).

The use of greenbelts is one of the measures that some countries have adopted to control urban sprawl (A. T. Han, 2019; 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). Among the countries in which greenbelts are popular are Germany and the UK (Baing, 2010; Kovács et al., 2019).

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); while 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” (A. T. Han, 2019, p. 301).

To address this dispute between opposing arguments about the general (non-)effectiveness of greenbelts, this research aims at unfolding the potency of this ploy in curbing urban sprawl and providing a comprehensive view on the functionality of the greenbelts, specifically in European cities in several population size categories, using Weighted Urban Proliferation (Jaeger and Schwick, 2014) and Weighted Sprawl per Capita (Behnisch et al., subm.) metrics.

There are multiple reasons for the selection of European cities:

1) Most of the existing literature in the context of 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 condition of urban sprawl in a few specific areas as case studies that do not allow for generalizations (e.g., H. Han and Go, 2019; Xie et al., 2020).
2) The studies available about greenbelts have mainly analyzed the cities or regions with greenbelts without comparing them to their counterparts without this feature, i.e., no control sites.
3) According to the United Nations, Europe is among the most urbanized geographic regions in the world with 74 percent of the population living in urban areas in 2018 (United Nations, 2019); and it has been shown that 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.

4) Interest in studying urban issues at the European level has been relatively low according to Kasanko et al. (2006), which makes focus on cities in this continent worthwhile.

We hypothesized that the (1) European cities having put greenbelts in place are generally less sprawled than cities without greenbelts; (2) urban sprawl has increased more slowly in European cities that have greenbelts than in those without greenbelts; (3) and greenbelts are more effective in controlling 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 greenbelts will be more pronounced. The analysis covers a 9-year timeframe, from 2006 to 2015, and the start and end points separately.

3.2 Methods

3.2.1 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 (Tab. 2), so that they are representative of European cities of differing sizes. The cities were spotted 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 greenbelts were selected correspondingly within the same countries, so that an equal distribution of cities with and without greenbelts would allow for a balanced comparison (Tab. 2). The minimum population size of cities to be considered was approximately 100,000 people.

The population data at the city level were procured from the Eurostat 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" (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" (European Commission, n.d.).

Since it was important for the cities without greenbelts 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. A), 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.

3.2.2 Measurement of urban sprawl

The method of Weighted Urban Proliferation (Jaeger & Schwick, 2014) and Weighted Sprawl per Capita (Behnisch et al., subm.) served 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 is compounded of three components including 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 to include highly utilized office buildings because they are not considered as sprawled areas. Consequently, higher numbers of inhabitants and jobs in a certain built-up area would manifest in a lower land uptake per person (Jaeger & Schwick, 2014).

While *WUP* denotes how much sprawl exists per square meter of landscape, weighted sprawl per capita (*WSPC*) indicates how much each person (inhabitant or job) contributes to urban sprawl on average (Behnisch et al., subm.). The value of *WSPC* represents how much urban sprawl is associated on average with each job or individual living in the reporting unit (Behnisch et al., subm.). The two metrics are related according to the equation $WSPC = (A_{\text{reporting unit}}/N_{\text{inh+job}}) \cdot WUP$.

Both metrics are intensive metrics, meaning that they can be applied to and compared between distinct landscapes regardless of their sizes.

Quantifying the extent of sprawl demands determining a maximum distance 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 (Nazarnia et al., 2016b). Based on this concept, two points only contribute to urban sprawl when located within one another's horizon of perception, and their contribution is higher when they are farther apart (Jaeger at al., 2010b). In this analysis, *HP* includes a buffer of 2 km around the city boundaries (as done in the European study EEA & FOEN, 2016).

Table 2 The population sizes and areas of the 60 European cities with and without greenbelts 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: more than 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: more than 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
	8	Cologne, Germany	1,046,680	407.3	8	Naples, Italy	978,399	118.7
Medium-Large: between 500,000 and 1,000,000	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
	18	Bradford, UK	529,666	367.1	18	Antwerp, Belgium	515,593	202.7
Medium: between 96,000 and 500,000	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	Munster, 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

3.2.3 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. B). The impervious layers provide imperviousness value ranging from 0% to 100%. The threshold for separating built-up and non-built-up cells was set at 30% based on the comparative study by Orlitová et al. (2012).

The population data and total numbers of jobs for each city were collected from the Eurostat *City statistic (urb)* database (European Commission - Eurostat, 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 (European Commission - Eurostat, 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 correction factor for converting the part-time jobs into their full-time equivalents (App. C). For the cities with missing data in the target years, the population sizes and jobs were estimated using a linear interpolation between other years where possible. In some cases, they needed to be calculated via extrapolation based on the ratio of increase in the following or previous years. Job data for the Polish cities was 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 the Eurostat *urban audit* database (European Commission - Eurostat, 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.

Quantification of the degree of urban sprawl (*WUP* and its components) was performed using the Urban Sprawl Metrics (USM) toolset, a GIS tool available from the WSL website[2], which uses three sets of input data including a binary map of built-up areas, the map of the boundaries of reporting units, and the numbers of inhabitants and jobs corresponding to the reporting units (Nazarnia et al., 2016b). After calculating the changes between 2006 and 2015 and between groups of cities with and without greenbelts, 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 component separately.

Our research consists of two separate analyses: (1) "Temporal change analysis" that examines 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 greenbelts in two particular years (2006 and 2015).

[2] Available at https://www.wsl.ch/de/services-und-produkte/software-websites-und-apps/urban-sprawl-metrics-tool-usm.html

3.2.4 City size adjustment for comparison of cities of differing sizes

WUP is an intensive metric, and 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 close along the built-up areas. Such differences convolute a fair comparison of the cities. Even when the population size and the amount and spatial pattern of the built-up areas of two cities are the same, the *PBA* of the two cities will differ. In a situation in which the status of built-up areas are similar in two cities, but the boundaries and area sizes differ, the value of *WUP* will be lower in the city whose boundary is located farther away as a result of lower *PBA*. Therefore, it is necessary to rescale the city boundaries to make the cities comparable on an equal footing.

For this purpose, we used the relationship between the 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. 5). In the cases in which the adjusted city size is greater than the original area, this corresponds to adding empty space with no built-up areas and no population. Hence, the only component that would be subject to adjustment 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 in which the area shrank due to the adjustment lost any built-up areas, i.e., the boundaries are simply drawn somewhat closer around the built-up areas, and population stayed the same as well. The adjusted city size was applied for both reference years, and *PBA* and *WUP* were recalculated for the comparison analysis of each year. The corresponding values of the new metrics are referred to as adjusted *PBA* and adjusted *WUP*.

City size adjustment was only developed and applied for the comparison analysis. This adjustment was not needed for the change analysis since the cities were compared to themselves, and the boundaries stayed the same when we calculated the difference over time.

For comparison, the analysis was also conducted on the results without adjusting city size. We found broadly similar results, but the differences between the cities with and without greenbelts were less pronounced (and statistically less significant).

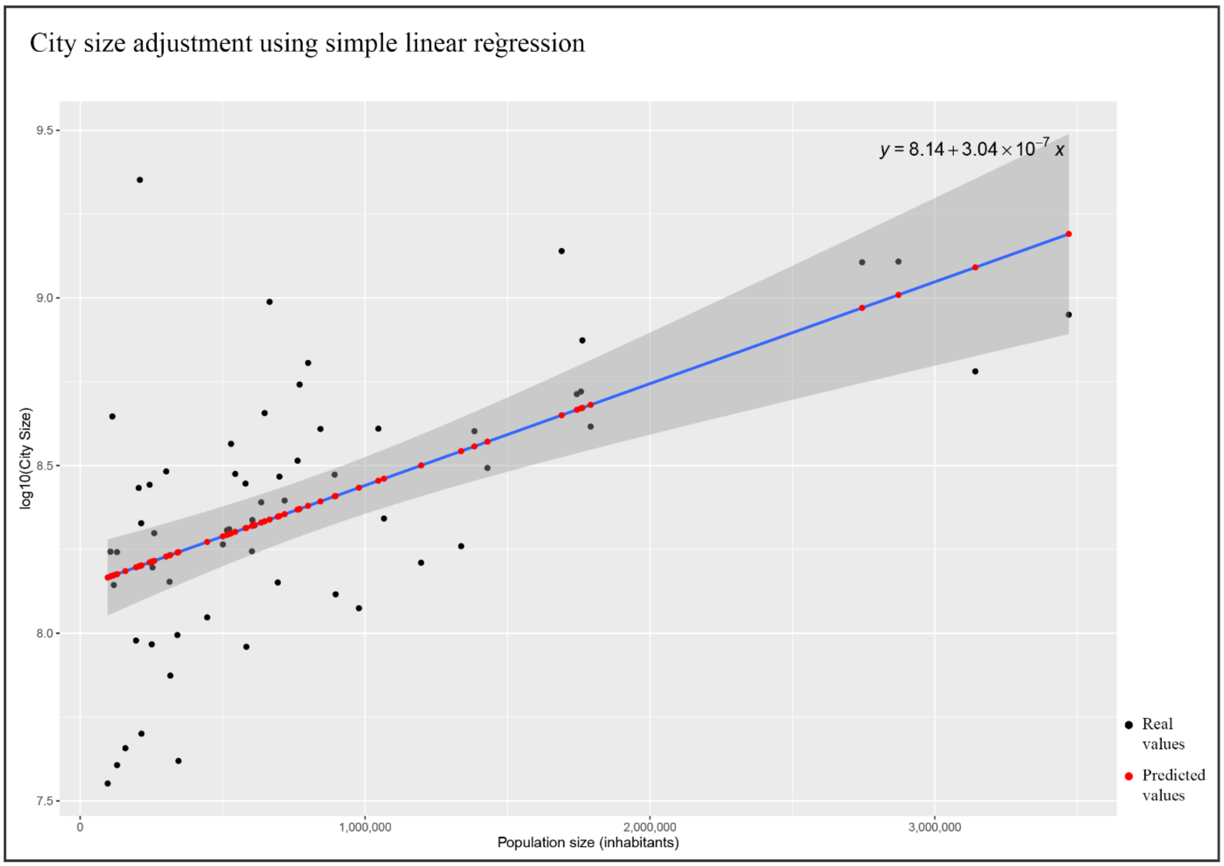

Figure 5 City size adjustment: Average city size as a function of population size ($R^2 = 0.35$).

3.3 Results

3.3.1 Temporal changes in urban sprawl between 2006 and 2015

3.3.1.1 Sprawl in relation to the population: *WSPC*

The absolute and relative changes in *WSPC* between 2006 and 2015 revealed significant differences between the two groups of cities with and without greenbelts, as indicated by the differences in the means and in the medians (Tab. 3). The absolute average contribution of each person to urban sprawl decreased almost three times as strongly in cities with greenbelts than those without: The mean decrease in *WSPC* in cities without greenbelts was 97.0 UPU/(inh or job) while in cities with greenbelts, the mean decrease was 273.0 UPU/(inh or job). The average relative changes in *WSPC* in cities with and without greenbelts were in opposite directions, showing the average contribution of each person to urban sprawl has increased by 24.2% in cities without greenbelts, while it decreased by 27.3% in the cities having greenbelts (Tab. 3). This difference in direction between the average relative changes in *WSPC* in cities with and without greenbelts is mainly due to great absolute reductions in *WSPC* values in few specific cases, as well as small relative decreases or great relative increases in *WSPC* values in the cities without greenbelts, which together led to an overall average relative increase in *WSPC* (see more detailed explanation in the 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 greenbelts 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 greenbelts, but decreased in more than half of the cities with greenbelts.

These findings were also supported by the test of proportions. The proportion of cities in which *WSPC* decreased differed significantly between the two groups of cities. The value of *WSPC* decreased in 27 cities, i.e., in 90% of the 30 cities with greenbelts. This proportion is more than twice that of the cities without greenbelts, for which *WSPC* decreased, which was 43% of the 30 cities. 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 absolute changes in these cities were larger in the cities without greenbelts (-532.1 UPU/(inh or job)) than with greenbelts (-306.9 UPU/(inh or job)), because very high absolute decreases in a few cites without greenbelts such as Antwerp, Lincoln, and Leipzig, strongly affected the mean (Fig. 6). The difference, however, was not statistically significant (see detailed information and results in Apps. D and E).

Such strong decreases in the cities without greenbelts were due to specific regulations, policies, or other measures that were 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" of more than 20 municipalities to jointly improve the attractiveness of the region. With the GRL as an inter-municipal association, the region has worked out a locational advantage over other regions (Grüner Ring Leipzig, n.d.). Antwerp and Lincoln, similarly, demonstrated remarkable decreases in land uptake per person, using their settlement areas more efficiently (i.e. housing more people and employees), causing strong reductions in sprawl.

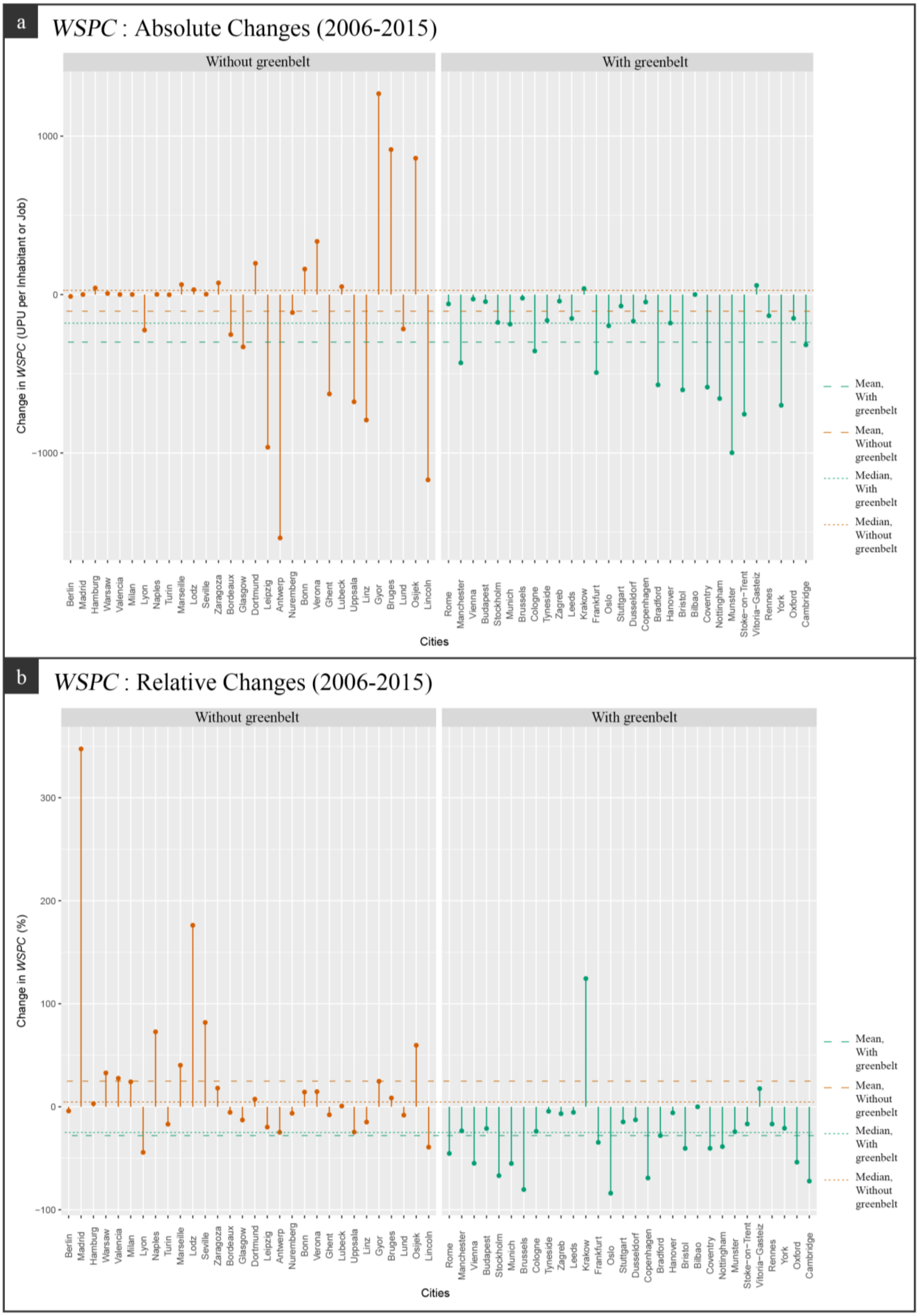

Figure 6 Absolute (a) and relative changes (b) in *WSPC* in the cities without greenbelts (orange) and with greenbelts (green), sorted by population size in descending order.

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

Similar to the changes in *WSPC*, *WUP* decreased in 27 (90%) of the cities with greenbelts. The corresponding proportion for the cities without greenbelts was remarkably lower with only 36.7% (Fig. 7). Among all the cities in which *WUP* decreased, the relative reduction was significantly stronger in cities with greenbelts (30.8%) than in those without (14%).

The differences in the changes in *WUP* between the two groups of the 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/m^2 in the cities without greenbelts, whereas it was reduced by 0.72 UPU/m^2 in the cities with greenbelts. Similar to *WSPC*, the average relative changes in *WUP* in cities with greenbelts were in the opposite direction of the average relative changes in cities without greenbelts. While urban sprawl per square meter of landscape increased by 29.2% in cities without greenbelts, it was reduced by 22.6% in cities with greenbelts (Tab. 3).

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

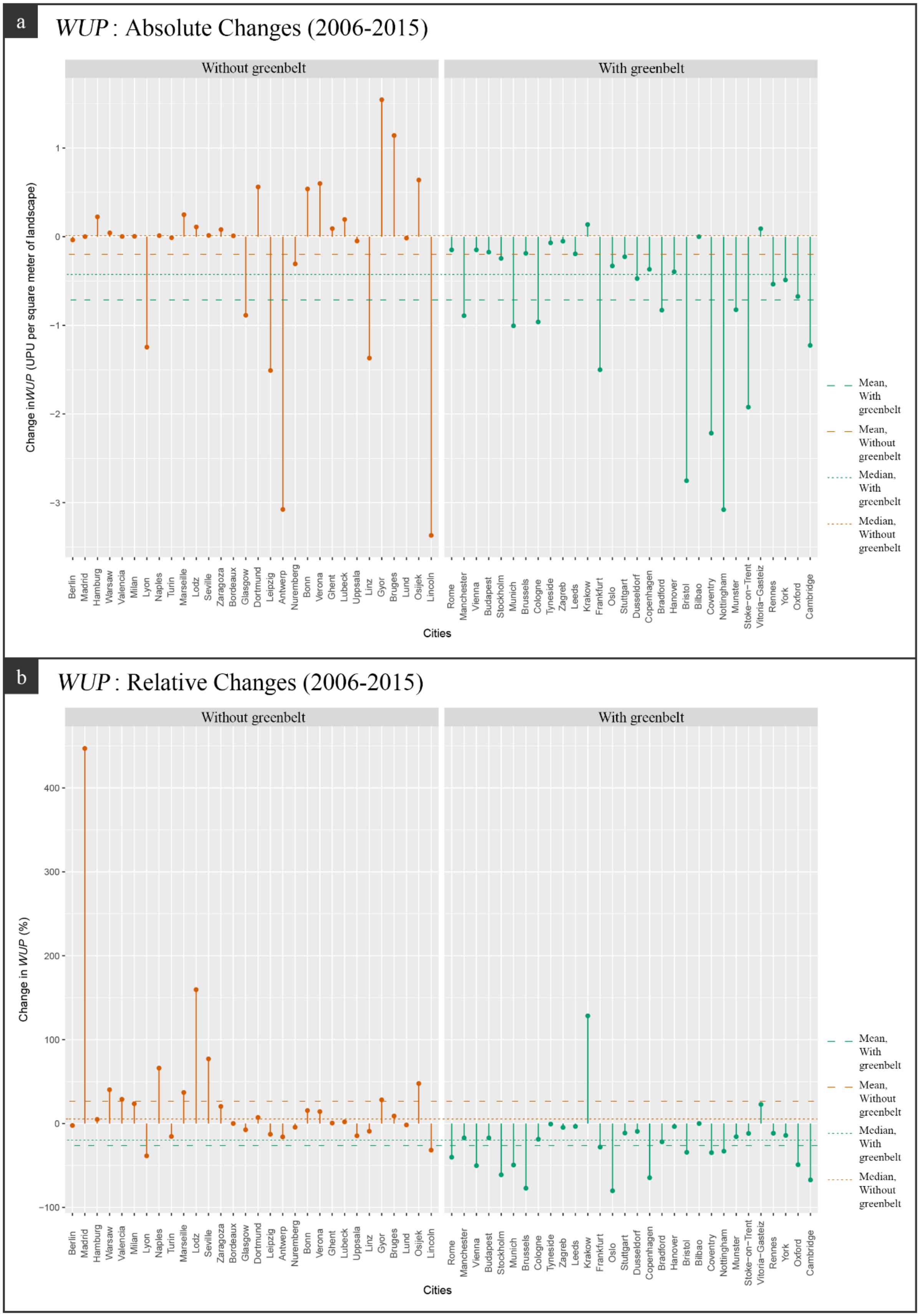

Figure 7 Absolute (a) and relative changes (b) in *WUP* in the cities without greenbelts (orange) and with greenbelts (green), sorted by population size in descending order.

Table 3 Results of the statistical analysis on the absolute and relative changes in urban sprawl in the two groups of cities.

Tests		Outputs Group 1: with greenbelt Group 2: without greenbelt	Changes in Urban Sprawl (2006 – 2015)			
			WSPC **Absolute Changes** (UPU per inhabitant or job)	***WSPC*** **Relative Changes** (%)	***WUP*** **Absolute Changes** (UPU per m^2 of landscape)	***WUP*** **Relative Changes** (%)
Kruskal-Wallis test	For differences between the means	*p*-value	0.012	0.000018	0.00019	0.0000049
		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	*p*-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		*p*-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		*p*-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

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

To test our third hypothesis, we also looked at the changes as a function of population size (Fig. 8). Running linear regressions and comparing the differences in slopes for relative and absolute changes in *WSPC* and *WUP* using ANOVA, we found that the differences in slopes between the two groups of cities with and without greenbelts 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)).

Looking more closely into the cities of larger population sizes, in the very large and large city 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 greenbelts. In relative terms, *WSPC* decreased by 46.4% in the cities with greenbelts, i.e. nearly halved between 2006 and 2015. A similar pattern was observed for *WUP* with an absolute decrease by 0.47 UPU/m^2 and relative decrease by 41.4% in the cities with greenbelts (App. F).

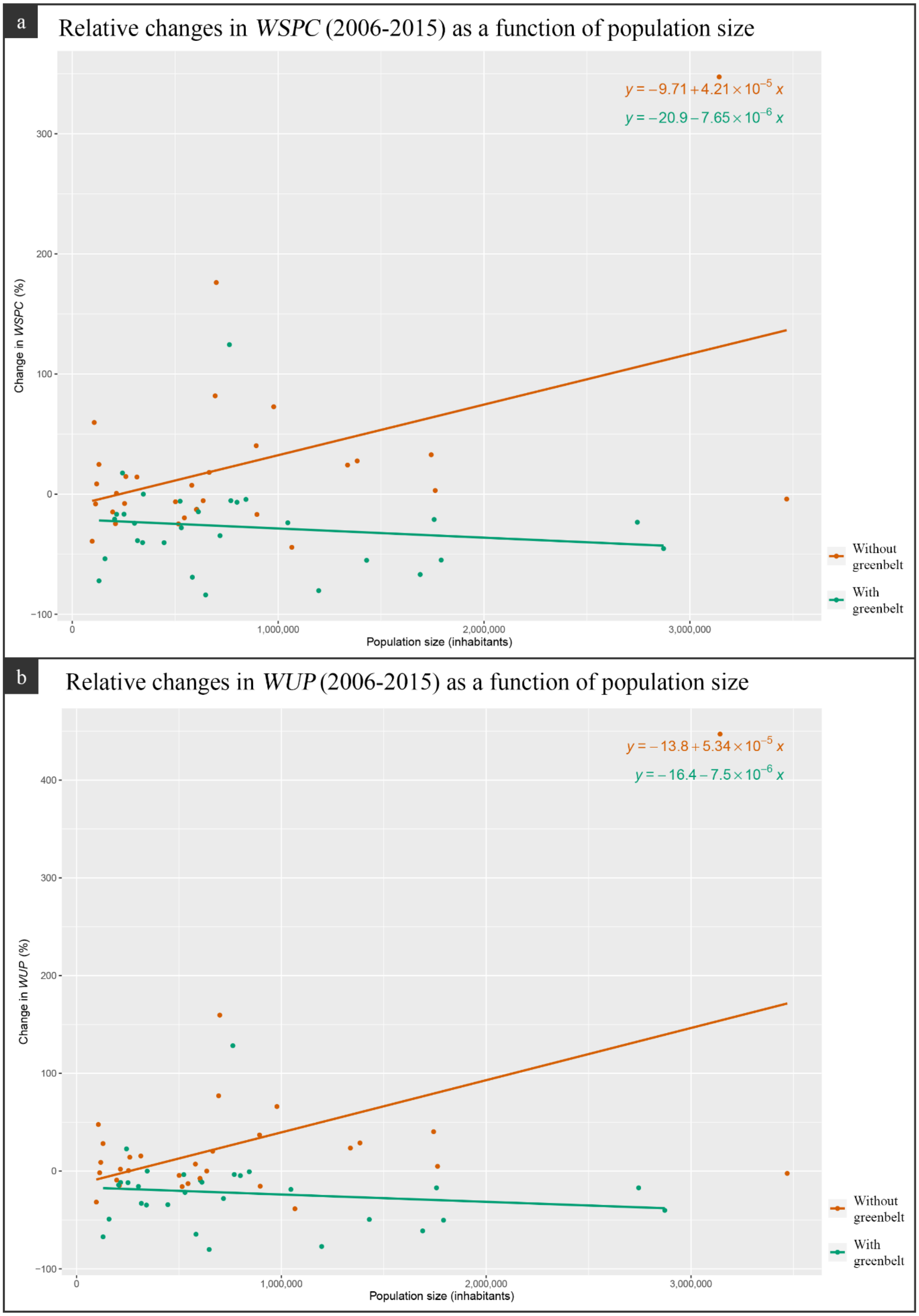

Figure 8 Relative changes in (a) *WSPC* and (b) *WUP* in the cities without greenbelts (orange) and with greenbelts (green) as a function of population size (Orange: R^2-*WSPC* = 0.22 and R^2-*WUP* = 0.25; Green: R^2-*WSPC* = 0.02 and R^2-*WUP* = 0.02). See App. G for absolute changes.

3.3.1.3 Changes in the three components of sprawl: *LUP*, *PBA*, and *DIS*

The strongest and highly significant results of *LUP* divulge the most important cause of changes in the level of urban sprawl in cities with greenbelts (Tab. 4) While the average value of *LUP* decreased in both groups of cities, the decrease was 17 times higher in cities with greenbelts (by -5.88 compared to -0.35 m^2 /(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 greenbelts. The difference between relative changes in *LUP* was statistically more significant compared to the absolute changes (Tab. 4).

The difference between the median changes was also highly significant. The mid-value of changes in *LUP* was negative in the cities with greenbelts, indicating a reduction in *LUP* in at least half of the cities in this group, while its counterpart in the cities without greenbelts still fell within positive range.

In fact, the proportion of cities in which *LUP* decreased was considerably greater in the group of cities with greenbelts. While 90% of the cities with greenbelts exhibited a reduction in *LUP*, it decreased in only 43% of the cities without greenbelts (Fig. 9).

In contrast, *PBA* and *DIS* did not show considerable differences between the two groups (Figs. 10 and 11). *PBA* demonstrated only a slight influence on the differences in the changes in urban sprawl between the groups. While average *PBA* increased in all cities regardless of the presence of a greenbelt, it augmented 1.77 times more strongly in the cities without greenbelts than in those with greenbelts in terms of relative changes, and this difference was statistically significant. Average changes in *DIS* were very low and exhibited modest increases in both groups of cities. These increments were slightly larger in the cities without greenbelts, but the difference was not statistically significant.

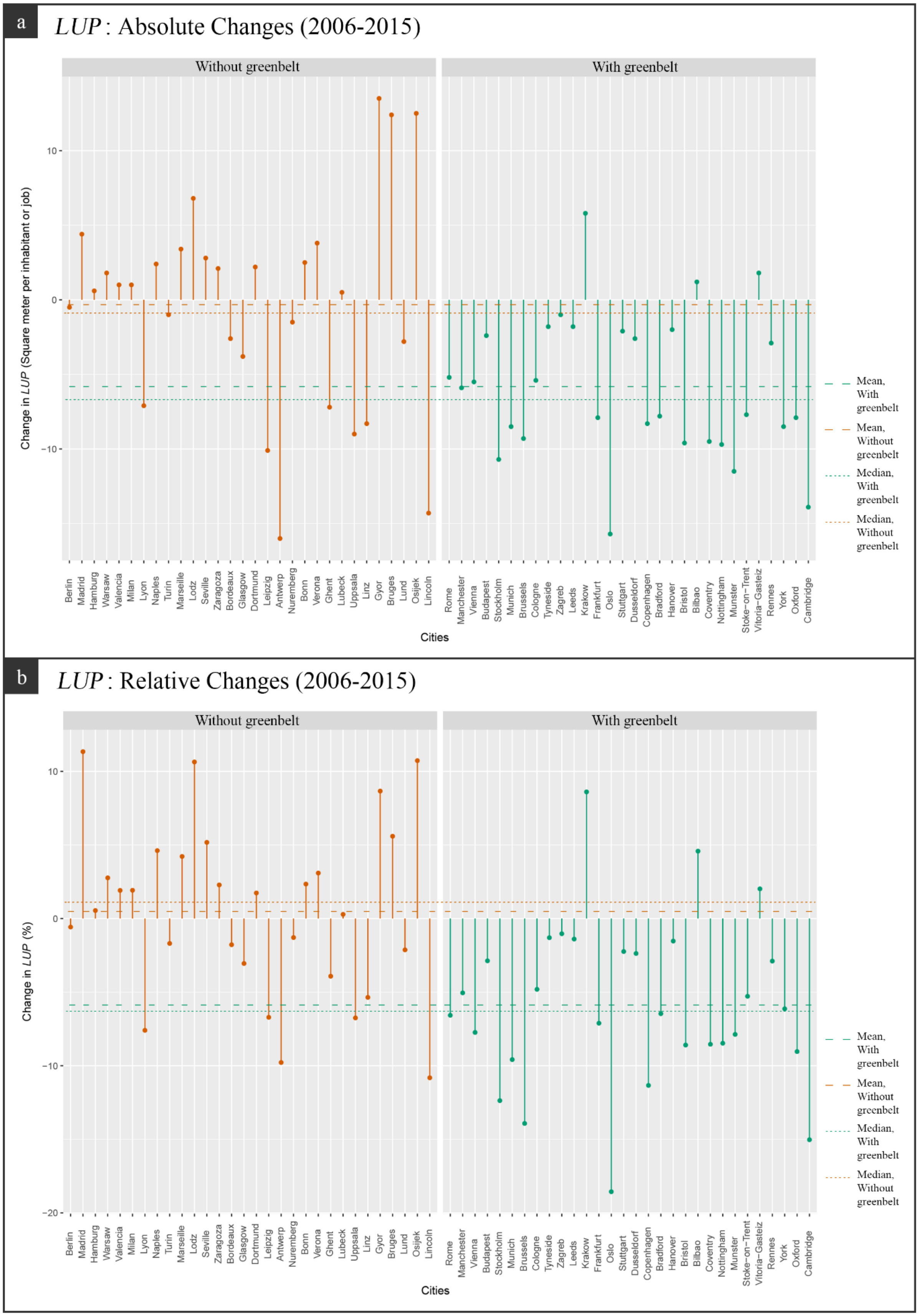

Figure 9 Absolute (a) and relative changes (b) in *LUP* in the cities without greenbelts (orange) and with greenbelts (green), sorted by population size in descending order.

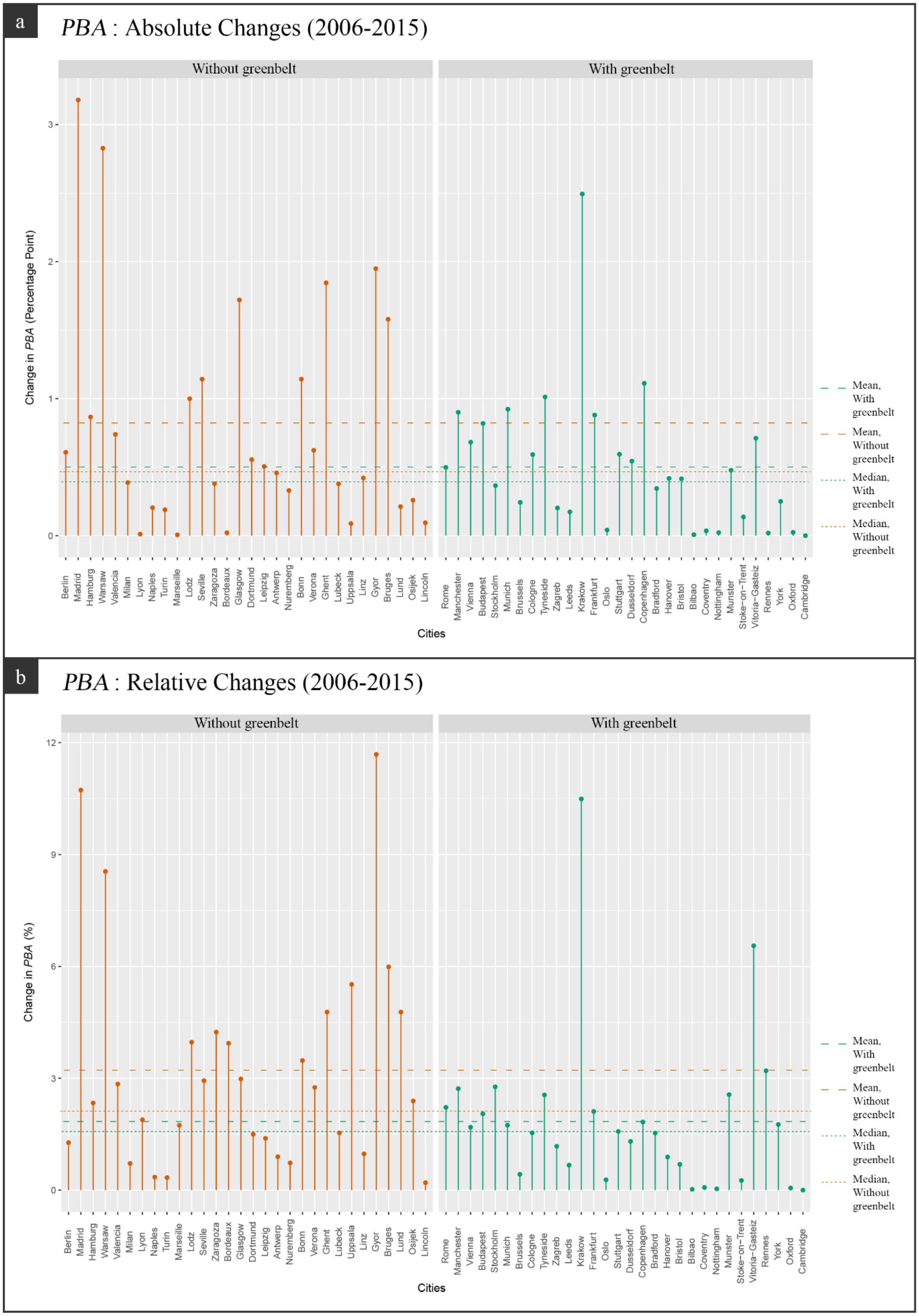

Figure 10 Absolute (a) and relative changes (b) in *PBA* in the cities without greenbelts (orange) and with greenbelts (green), sorted by population size in descending order.

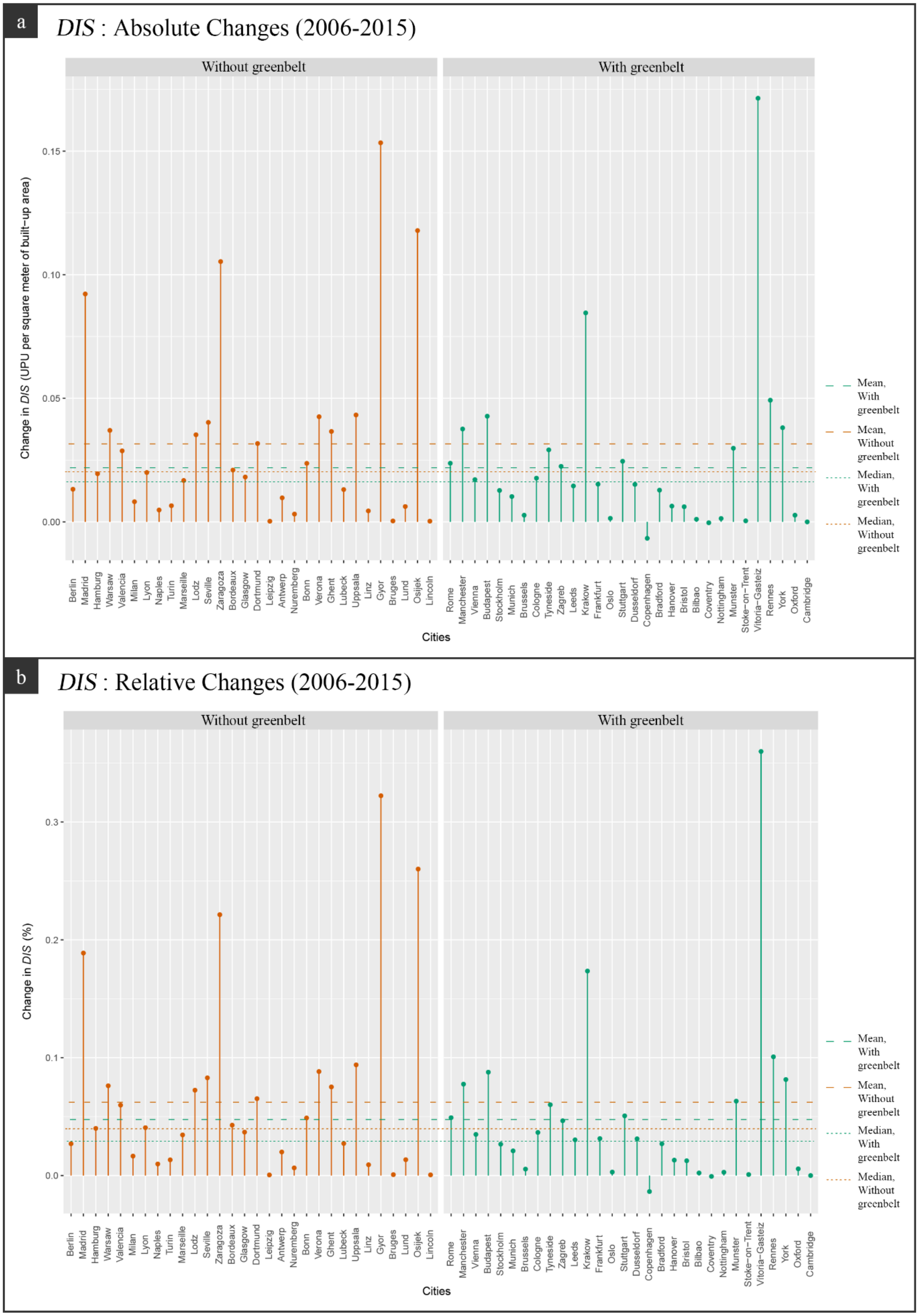

Figure 11 Absolute (a) and relative changes (b) in *DIS* in the cities without greenbelts (orange) and with greenbelts (green), sorted by population size in descending order.

Table 4 Results of the statistical analysis on absolute and relative changes in the three components of urban sprawl in two groups of cities.

Tests	Outputs	Changes in the Components of Urban Sprawl (2006 – 2015)					
	Group 1: with greenbelt Group 2: without greenbelt	***PBA* Absolute Changes** (Percentage Point)	***PBA* Relative Changes** (%)	***DIS* Absolute Changes** (UPU per m^2 of built-up area)	***DIS* Relative Changes** (%)	***LUP* Absolute Changes** (m^2 per inhabitant or job)	***LUP* Relative Changes** (%)
Kruskal-Wallis test / t-test For differences between the means	*p*-value	0.21	0.014	0.22	0.21	0.00089	0.000083
	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 For differences between the medians	*p*-value	0.61	0.12	0.31	0.31	0.0048	0.00034
	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 For differences between the proportions of cities with decreased values	*p*-value	NA	NA	0.47	0.47	0.00037	0.00037
	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

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

3.3.2 Comparison between the two groups of cities for each year separately

3.3.2.1 Urban sprawl in 2006 and 2015 using *WSPC* and adjusted *WUP*

We compared the cities with and without greenbelts for each year separately, i.e., for 2006 (App. H) and 2015 (Fig. 12). The differences between the means (and between the medians) of *WSPC* and adjusted *WUP* were considerable with much greater values in the cities without greenbelts than those with a greenbelt (Tab. 5), but they were not statistically significant for the sample size available in this study. This comparison covered a large range in population size and exhibited high variability in the values (Fig. 12). Due to this large variability in the values, a larger sample size would be needed to achieve statistical significance of the differences between the means (and the medians).

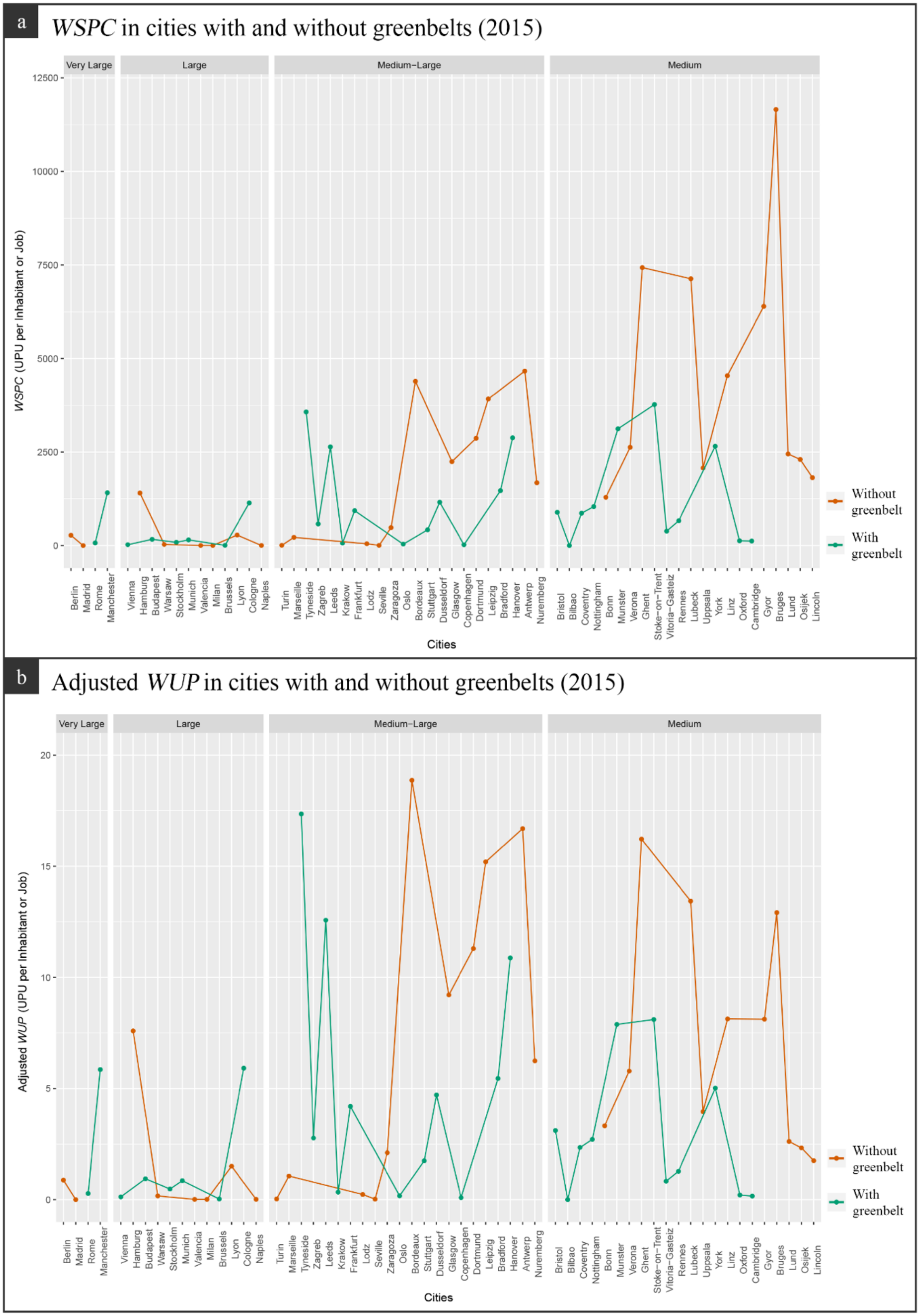

Figure 12 Diagram of (a) *WSPC* and (b) Adjusted *WUP* values in the cities without greenbelts (orange) and with greenbelts (green), in 4 population-size categories (2015) (A line graph is used to group the cities for better visibility).

Table 5 Results of the statistical analysis comparing the mean and median level of urban sprawl between the groups of cities with and without greenbelts in 2006 and 2015.

Tests	**Outputs** Group 1: with greenbelt Group 2: without greenbelt	**Urban Sprawl**			
		WSPC (UPU per inhabitant or job)		**Adjusted *WUP*** (UPU per m^2 of landscape)	
		2006	**2015**	**2006**	**2015**
Kruskal Wallis test For differences in the means	*p*-value	0.391	0.165	0.734	0.344
	Mean in group 1	1288.76	1015.715	4.16	3.54
	Mean in group 2	2504.65	2407.629	5.74	5.66
Mood's Median test For differences in the medians	*p*-value	0.306	0.1245	1	0.609
	Median in group 1	708.77	620.9881	2.44	2.05
	Median in group 2	1617.11	1746.176	2.77	2.97

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

In contrast, according to the analysis of three population-size categories of cities, the differences between the medium-sized cities (with less than 500,000 inhabitants) with and without greenbelts were statistically significant for both 2006 and 2015 (Tab. 6).

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, in the medium-sized cities were marginally significant in 2006 and significant in 2015 (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 the medians of *WSPC* and adjusted *WUP* were greater in the cities without greenbelts than in the ones with greenbelts for the medium-large cities in both years, the results were not statistically significant, likely due to small sample size (10 cities in each group). Consequently, 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 greenbelts, 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 greenbelts, this decrease was much weaker than in the cities with greenbelts. The same pattern was observed for the median and mean differences in the *WSPC* values (see Discussion).

Table 6 Results of the statistical analysis comparing the level of urban sprawl between the groups of cities with and without greenbelts 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.

Tests	**Outputs** Group 1: with greenbelt Group 2: without greenbelt	**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**		
		Very Large and Large	**Medium-Large**	**Medium**	**Very Large and Large**	**Medium-Large**	**Medium**	**Very Large and Large**	**Medium-Large**	**Medium**	**Very Large and Large**	**Medium-Large**	**Medium**
Kruskal Wallis test / t-test For differences in the means	*p*-value	0.115	0.398	0.016	0.248	0.376	0.0053	0.093	0.974	0.087	0.248	0.508	0.01975
	Mean in group 1	545.50	1438.25	1679.83	382.30	1252.19	1239.90	2.40	5.99	3.61	1.81	5.48	2.88
	Mean in group 2	272.83	2123.17	4509.26	249.62	1865.77	4518.94	1.34	7.80	6.89	1.27	7.36	7.14
Mood's Median test For differences in the medians	*p*-value	0.333	0.677	0.037	0.333	0.677	0.037	0.333	0.677	0.211	0.333	0.677	0.037
	Median in group 1	237.65	1325.63	1449.54	119.87	932.26	865.11	1.18	5.19	3.59	0.66	4.19	2.35
	Median in group 2	11.40	1791.76	2983.71	15.41	1678.30	2626.99	0.06	6.53	5.06	0.09	6.24	5.78

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

3.3.2.2 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 the cities without greenbelts with 94.9 m^2/(inh. or job) and 111.8 m^2/(inh. or job), respectively ($p = 0.085$) (Tab. 7).

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

Table 7 Results of statistical analysis on the components of urban sprawl in 2006 and 2015.

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 For differences in the means	*p*-value	0.623	0.953	0.583	0.692	0.976	0.085
	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 For differences in the medians	*p*-value	0.306	1	0.306	0.306	1	0.1245
	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

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

Similar to the comparison of *WSPC* and adjusted *WUP*, the comparison of the three component for the three population-size categories revealed significant differences for the medium-sized cities. The average *LUP* values differed significantly between the two groups of cities in this population-size category (Tab. 8). 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 the great differences in *LUP*, i.e., denser built-up areas in the medium-sized cities with greenbelts.

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 greenbelts for neither of the population-size categories.

Table 8 Results of statistical analysis on the 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.

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 For differences in the means	*p*-value	0.245	0.9225	0.832	0.272	0.934	0.716
	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 For differences in the medians	*p*-value	0.333	0.677	0.677	0.333	0.677	0.677
	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

Tests	Outputs Group 1: with greenbelt Group 2: without greenbelt	Components of Urban Sprawl: *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 For differences in the means	*p*-value	0.318	0.433	0.156	0.299	0.402	0.158
	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 For differences in the medians	*p*-value	0.333	0.677	0.677	0.333	0.677	0.677
	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

Tests	Outputs Group 1: with greenbelt Group 2: without greenbelt	Components of Urban Sprawl: *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 For differences in the means	*p*-value	0.1	0.888	0.0079	0.263	0.7295	0.0026
	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 For differences in the medians	*p*-value	0.333	0.677	0.037	0.333	0.677	0.037
	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

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

3.4 Discussion

3.4.1 Temporal changes in urban sprawl and its components

Our analysis revealed that the greenbelts have been considerably effective in controlling urban sprawl in Europe at the city level. Despite the general observation that urban sprawl has increased unequivocally worldwide (EEA & FOEN, 2016; OECD, 2018), as reflected in our second hypothesis, our results showed that where greenbelts were put in place, urban sprawl has decreased substantially. Reductions were observed in the mean values of both *WUP* and *WSPC*, meaning that on average, sprawl per square meter of landscape as well as the contribution of each person to urban sprawl decreased between 2006 and 2015, absolutely and relatively, in the cities with greenbelts.

In contrast, the relative changes in the values of average *WSPC* and *WUP* indicated, on average, an increase in urban sprawl in the cities without greenbelts. The mean absolute changes in *WSPC* and *WUP*, however, displayed only minor decreases in the cities without greenbelts on average, i.e., remarkably weaker than the mean absolute decreases in the cities with greenbelts.

Two main reasons can explain why average sprawl decreased in absolute terms, while it increased in relative terms in the cities without greenbelts: (1) Great 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. To elaborate, the high 2006 values of *WSPC* and *WUP* in most of the cities without greenbelts led to low relative decreases even when *WSPC* and *WUP* greatly abated;

contrarily, for some cases such as Madrid where the 2006 values of *WSPC* and *WUP* were quite low, even slight absolute increases resulted in large relative increases. In contrast, most of the cities with greenbelts had fairly low *WSPC* and *WUP* values in 2006, and most of them decreased by 2015, hence, division of these changes by the low values of *WSPC* and *WUP* of 2006 resulted in rather large average relative decreases in these two metrics.

The effectiveness of greenbelts in curbing urban sprawl is also evident in the proportions of cities in which *WSPC* and *WUP* decreased. Not only had both metrics demonstrated decreases in most of the cities with greenbelts as opposed to the cities without greenbelts, but the average relative reductions in the metrics 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 and *LUP* demonstrated strong average absolute and relative reductions, in the cities with greenbelts, which is a result of stronger densification of the existing built-up areas that on average had a stronger influence than the expansion of built-up areas in these cities. Greater average relative increase in *PBA* also contributed to higher values of *WSPC* and *WUP* in the cities without greenbelts. *DIS* is the average weighted distance between every two random points in built-up areas and captures the spatial arrangement of built-up areas (Jaeger et al., 2010b). Negligible changes in *DIS*, hence, seem sensible as the existing buildings cannot be moved around easily, and their spatial arrangement cannot be simply altered.

When we examined three population-size categories separately to find out where the greenbelts were most effective, the group of very large and large cities exhibited greater differences between the relative changes in the cities with and without greenbelts. In addition, regression of the changes in urban sprawl as a function of population size revealed that the greenbelts were more effective in controlling urban sprawl in cities with larger population sizes in terms of relative changes, meaning that relative differences in the changes in *WSPC* and *WUP* between cities with and without greenbelts were more pronounced in cities in which the population was larger. This outcome confirmed our hypothesis in terms of relative changes, while it did not support it in terms of absolute changes.

It is noteworthy that both metrics decreased in all 8 cities of the very large and large category with greenbelts, but in only 2 of the cities without greenbelts (25%), showing that the greenbelts were effective in reducing urban sprawl in 100% of the cities with greenbelts in this category. The cities in the medium-size category also demonstrated significant results, but the differences between the cities with and without greenbelts were statistically more significant in the group of very large and large cities, meaning that even with a small sample size in this category, the differences between the cities with and without greenbelts were strong enough to be confirmed.

3.4.2 Comparison of urban sprawl and its components for each year separately

Unlike the changes between 2006 and 2015, neither of the *WSPC* and adjusted *WUP* metrics provided statistically significant results for 2006 nor 2015 for this sample size. Although the average *LUP* value demonstrated a marginally significant difference in 2015, this difference was not strong enough to affect the values of *WSPC* or adjusted *WUP*. However, there were large differences as predicted by our hypothesis 1, i.e., greater values in the cities without greenbelts. 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 greenbelts for each year.

According to a power analysis, the minimum sample size needed for an 80% chance of detecting differences between the cities with and without greenbelts for the 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 first calculating the effect sizes, which indicate the magnitude of the differences, 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 in this continent at this time.

While the numbers of cities in each population-size category were much lower (i.e. 8 very large and large, 10 medium-large, and 12 medium), the cities of medium population size displayed significant differences between the average sprawl values of the groups of cities with and without greenbelts for both years, which was mainly a response to the substantial differences between the average *LUP* values. Insignificant results for the medium-large city category, however, appear to be mainly a result of 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/m^2 in 2006 compared to 0.54 in 2015 UPU/m^2 for adjusted *WUP*), showing that the decrease in the cities with greenbelts was much stronger. Using the annual linear rate of decrease for each group in this population-size category, we envisioned that if the current trend continues, the group of large and very large cities will evince lower *WSPC* and adjusted *WUP* values in the cities with greenbelts than those without greenbelts in 2024 and 2025, respectively, similar to the other population-size categories. With the same reasoning, it is likely that the cities in this category would demonstrate lower *LUP* values in the cities with greenbelts than the ones without in 2031.

A similar result would then manifest for the adjusted *PBA* mean values, regardless of population size, in nearly four decades, when the amount of built-up area in the cities without greenbelts will exceed that in the cities with greenbelts, opposite to the current situation.

3.4.3 Examples: Vienna, Coventry, Greater Manchester

Three examples serve to illustrate the results.

3.4.3.1 Vienna

The greenbelt of Vienna dates back to 1905 when the Viennese Forest-and-Meadow Belt agreement was reached by the city council as a means of nature conservation (Breiling & Ruland, 2008). Currently, more than 50% of Vienna's area is covered by green space (City of Vienna, 2015). Vienna has strong autonomy compared to other cities in Austria, and its status of a federal state made it possible for Vienna to evolve its own policies and strategies, including plans to safeguard the green network (Mocca et al., 2020). Following the One-Thousand-Hectare Programme endorsed in 1994 with the aim of protecting the northeastern landscape of the city and developing the forest-and-meadow belt, the Vienna Greenbelt Masterplan was officially adopted in 1995 (Breiling & Ruland, 2008; City of Vienna, 2000, 2015).

The greenbelt of Vienna has proven to be a successful means for controlling urban sprawl in this city as demonstrated by the changes in *WSPC* and *WUP* values between 2006 and 2015.

Despite a slight increase in *PBA* (Fig. 13) and a minor rise in *DIS*, *LUP* demonstrated a notable drop, leading to significant decreases in *WSPC* and *WUP* (Tab. 9).

The most important strategies used to establish the greenbelt were the consolidation of green spots into wider protected areas, the acquisition of new land for extending the green spaces, and the promotion of the "second-class open spaces" to "first-class green recreation areas" (Breiling and Ruland, 2008).

To continue this positive trend, several major visions and objectives of expansion and preservation of the greenbelt have been elaborated in the Urban Development Plan (STEP) of Vienna. The Stadtentwicklungsplan (STEP), i.e., the Urban Development Plan of Vienna, is updated every 10 years since 1984 (1994, 2005, and 2015). The federal state of Lower Austria surrounds the federal state of Vienna. The long-term policy for the greenbelt is to maintain the existing green spaces and secondly to expand it into regions of the state of Lower Austria in order to more effectively protect these landscapes in a joint effort with the surrounding municipalities and avoid leapfrogging, and to modify the greenbelt policy into a policy at the regional level across two federal states (City of Vienna, 2015). Moreover, to protect and guarantee the persistence of farmlands as significant portions of the greenbelt, subsidies are to be allocated to the farmers in this sector (City of Vienna, 2000). The expenses of these measures have been covered by public funds complemented by grants from sponsors, and public-private partnerships (City of Vienna, 2000).

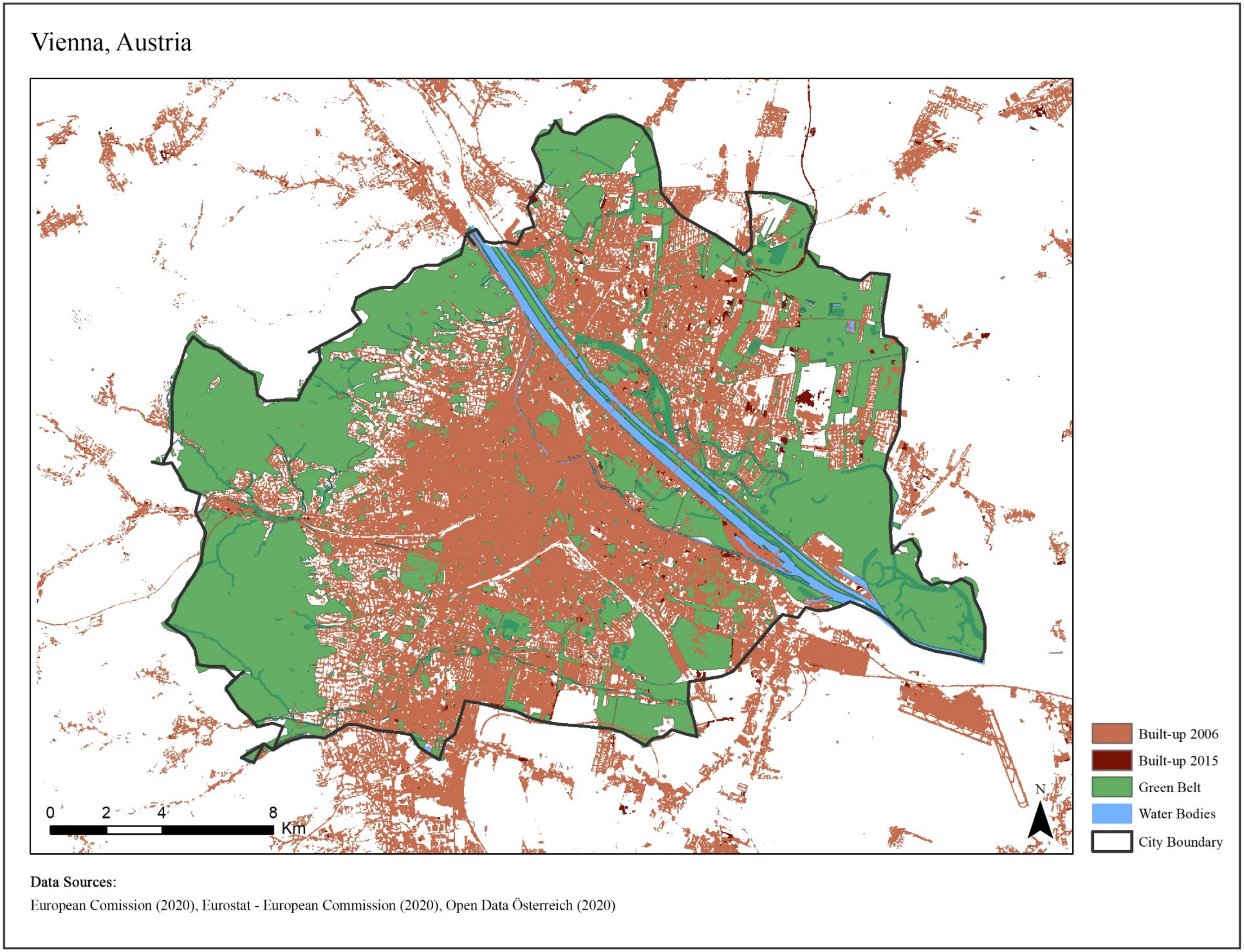

Figure 13 Map of Vienna, its greenbelt, and its built-up areas in 2006 and 2015 (European Commission, 2020; Eurostat - European Commission, 2020; Open Data Österreich, 2020).

3.4.3.2 Coventry

The greenbelt of Coventry is part of the West Midlands greenbelt (Land Use Consultant, 2015), which was first introduced in the West Midlands Structure Plan in 1982. It was modified in 1986 under the independent Coventry Green Belt Plan (Coventry City Council, 2014). To accommodate population growth due to increased employment number in Coventry, three small-scaled landscapes of ProLogis Park (Keresley), Whitley Park, and Browns Lane were detached from the greenbelt in the Unitary Development Plan of 2001 (Fig. 14), but the extent of the greenbelt has been untouched ever since (Coventry City Council, 2014).

According to the most recent Coventry Local Development Plan, the increase in population and job has been managed without permeating the designated greenbelt area throughout the years (Coventry City Council, 2014). Accommodating housing needs while keeping the greenbelt area intact has been effective in controlling urban sprawl, as supported by our results. The very low increment in *PBA* by less than 0.1% underlines that the urban development was very limited between 2006 and 2015. A considerable reduction in *LUP* reflects the densification of the existing developed areas within the city boundary, leading to substantial decreases of *WSPC* and *WUP*, respectively (Tab. 9).

The Coventry Local Development Plan envisions three scenarios to effectively respond to future population growth and accommodation demands, all of which address certain parts of the housing needs in locating new homes within the existing urban areas and brownfield land. For the remaining housing needs, the scenarios suggest three options: (1) “Protecting the greenbelt” by providing homes in Warwickshire; (2) “building within the boundary” by modifying the boundary of the greenbelt, which will damage the greenbelt and may have negative environmental impacts;

and (3) “sustainable growth” through combination of the first two scenarios, with construction on “least sensitive” and “least valuable” lands of the greenbelt area (Coventry City Council, 2014).

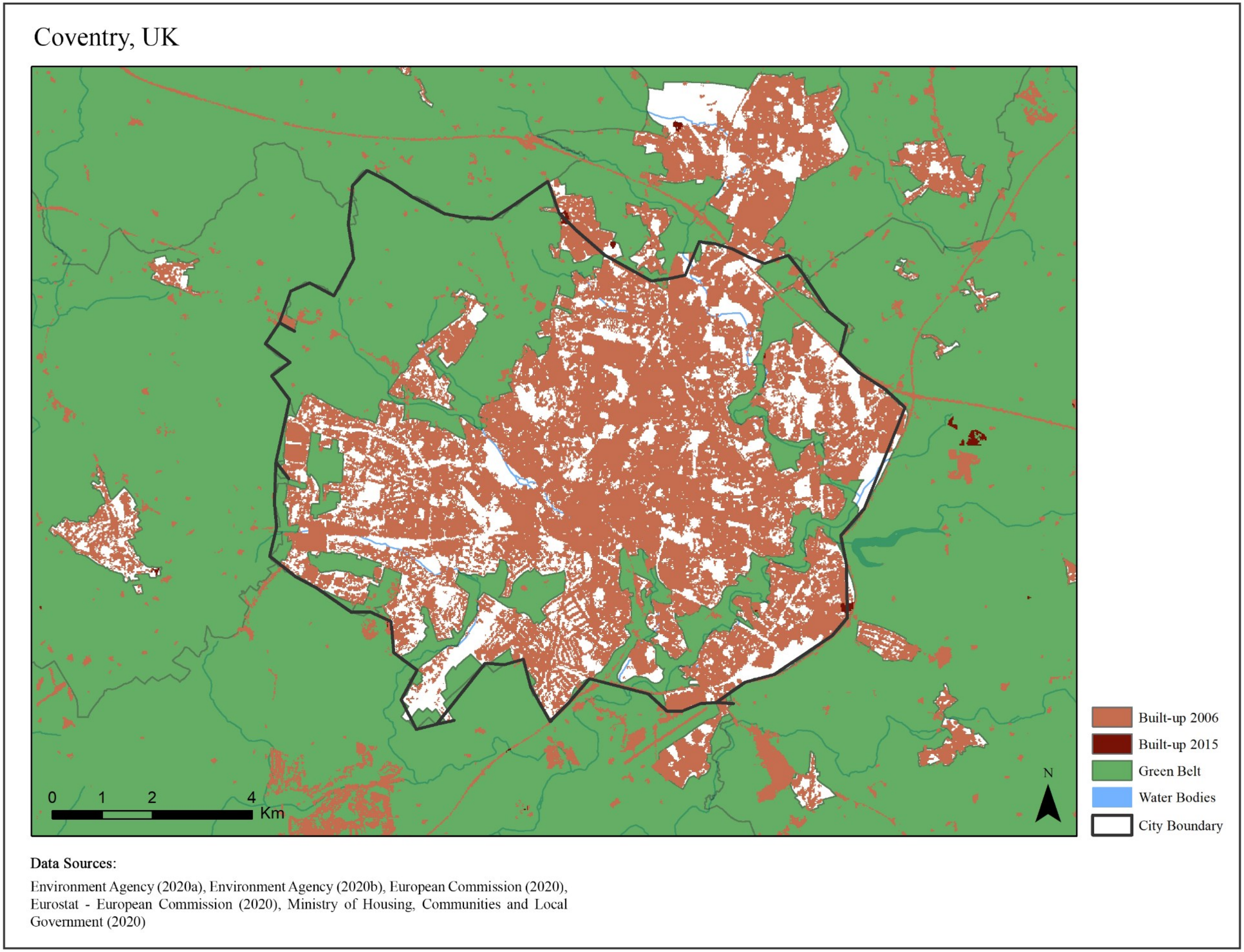

Figure 14 Map of Coventry, its greenbelt, and its built-up areas in 2006 and 2015 (Environment Agency, 2020b, 2020a; European Commission, 2020; Eurostat - European Commission, 2020; Ministry of Housing, Communities and Local Government, 2020).

3.4.3.3 Greater Manchester

The greenbelt of Greater Manchester was first established in 1984 and has been subject to amendments throughout the years. By 2015, a total area of 59,350 hectares (47% of the area of Greater Manchester) was covered by the greenbelt (Greater Manchester Combined Authority, 2019).

Between 2006 and 2015, *WSPC* and *WUP* decreased by 23.4% and 17.1%, respectively, in Greater Manchester (Tab. 9). Similar to most of the other cities with greenbelts, the main reason was a substantial reduction in *LUP* which affected the sprawl values more strongly than the moderate increase in *PBA*, part of which happened in the greenbelt zone (Fig. 15).

While the greenbelt had a considerable influence in curbing immoderate urban development in this greater city and helped the neighborhoods maintain their character, some landscapes will continue to be released from the greenbelt in the next 20 years due to increasing housing needs, according to the Greater Manchester Spatial Framework (GMCA, 2019). However, by adding a few new sites to the greenbelt, the net loss of the greenbelt will be halved in the next two decades. This proposal will ensure that no less than 45% of Greater Manchester will be covered by the greenbelt in the next 20 years (GMCA, 2019).

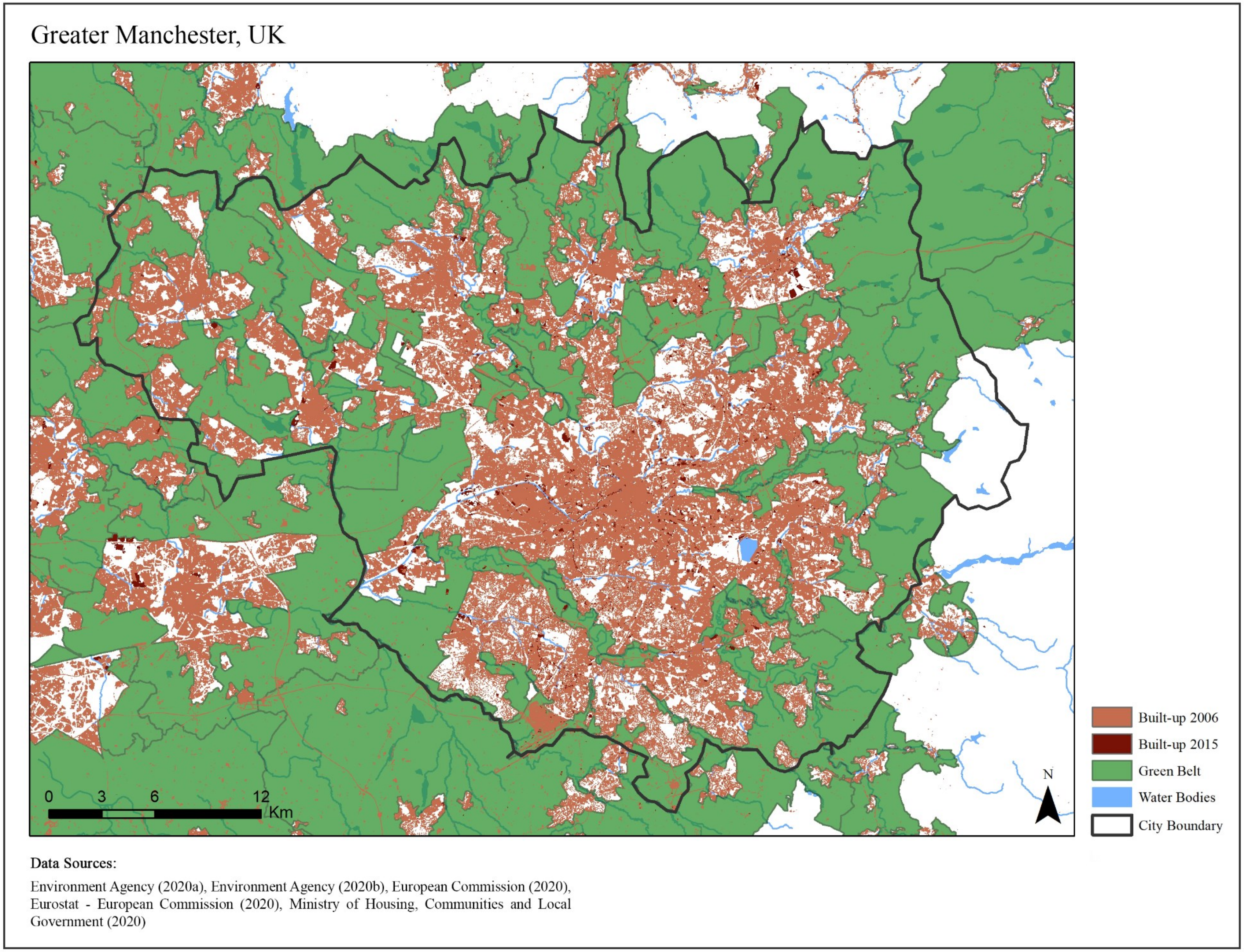

Figure 15 Map of Greater Manchester, its greenbelt, and its built-up areas in 2006 and 2015 (Environment Agency, 2020b, 2020a; European Commission, 2020; Eurostat - European Commission, 2020; Ministry of Housing, Communities and Local Government, 2020).

Table 9 Results for three examples of cities with greenbelts: Vienna, Coventry, and Greater Manchester.

City	Changes in Urban Sprawl (2006 – 2015)				Changes in the Components of Urban Sprawl (2006 – 2015)					
	WSPC **Absolute Changes** (UPU per inhabitant or job)	***WSPC*** **Relative Changes** (%)	***WUP*** **Absolute Changes** (UPU per m^2 of landscape)	***WUP*** **Relative Changes** (%)	***PBA*** **Absolute Changes** (Percentage Point)	***PBA*** **Relative Changes** (%)	***DIS*** **Absolute Changes** (UPU per m^2 of built-up area)	***DIS*** **Relative Changes** (%)	***LUP*** **Absolute Changes** (m^2 per inhabitant or job)	***LUP*** **Relative Changes** (%)
Vienna	-28.48	-54.87	-0.15	-50.23	0.68	1.69	0.02	0.03	-5.50	-7.74
Coventry	-584.43	-40.32	-2.22	-34.72	0.04	0.07	0.00	0.00	-9.50	-8.54
Greater Manchester	-431.03	-23.39	-0.89	-17.10	0.90	2.72	0.04	0.08	-5.90	-5.05

3.4.4 Comparison with other studies

A similar study by Xie et al. (2020) analyzed urban sprawl in three cities with greenbelts (Frankfurt, London, and Seoul) between 1975 and 2015, using the *WUP* metric. Their results showed that urban sprawl decreased in the inner-cities of Frankfurt and London, i.e., the area surrounded by the greenbelt. However, it increased in the outer area of the cities, i.e., the area beyond the greenbelt boundary within a 40-km buffer. In Seoul, the *WUP* value 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 case studies.

Focusing on 30 cities with greenbelts and comparing them to 30 counterparts and applying the same method (*WUP*), our results do not support the debate of leapfrogging development at the city scale (i.e., within the city boundaries), in contrast to the study by Xie et al. (2020). Xie et al. (2020) considered a very large buffer for each of the cities, which extended 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 zone 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 of the case studies (encompassing neighboring provinces or regions) do not signify sprawl at the city level. Those outer areas would clearly need to be controlled by additional measures, while expecting that Frankfurt's greenbelt would control sprawl in Darmstadt is unreasonable.

In contrast, we have taken into account in our calculations a buffer of 2 km (known as the horizon of perception, *HP*; Jaeger et al., 2010b), around the boundary of the city, which considers the greenbelt and potential development in it, and the area beyond the city boundary. In other words, the leapfrogging development is examined to some degree while keeping the analysis at the city scale. However, since the leapfrogging development beyond the city boundaries is more of a regional concept, the analysis of urban sprawl at the city scale with a 2-km buffer may not catch it properly. Our study was not designed to allow an analysis of leapfrogging development beyond this 2-km buffer around the city boundaries. Hence, considering case-specific wider buffers would more accurately address this issue.

Siedentop et al. (2016) analyzed greenbelts in Germany's regional plans, focusing on four regions of Dusseldorf, Hanover, Mittelhessen, and Stuttgart, considering "tightness" of greenbelts and their impacts on urban growth as the main indicators. This study suggested that greenbelts were effective in controlling urban growth at the regional scale. Among the seven cities with greenbelts we studied in Germany, Dusseldorf, Hanover, and Stuttgart were among the same regions studied by Siedentop et al. (2016), in which sprawl decreased over time. Our findings, therefore, were consistent with the results of their study in terms of the effectiveness of greenbelts, suggesting that they are promising means of urban growth management in Germany at both regional and city scales.

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 showed that they have been 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, a study by Nazarnia et al. (2016a) compared Montreal, Quebec City, and Zurich metropolitan areas using *WUP* metric, none of which have greenbelts. Nazarnia et al. (2016a) indicated that urban sprawl increased in all three cases between 1951 and 2011, but the increase was remarkably lower in Zurich compared to Montreal and Quebec City due to a much stronger public transportation system and rigorous planning regulations since 1979. Hence, to alleviate urban sprawl in Montreal and Quebec City, Nazarnia et al. (2016a) suggested the expansion of public transport and the increase in utilization density. Since greenbelts help densification according to our findings, they can be applied in Montreal and Quebec City, and even Zurich, as a means for increasing utilization density and lowering urban sprawl.

3.4.5 Strengths, limitations, and future research suggestions

To the best of our knowledge, this is the first study that assesses the effectiveness of greenbelts at curbing urban sprawl by comparing a considerable sample of cities with and without greenbelts. A wide range of population sizes is considered to comprise cities of varied 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).

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

3.5 Conclusion and recommendations

Urban sprawl is of great concern and subject to heated debate in a world of increasing urbanization, and its serious impacts have evoked attention in recent decades all over the planet. Multiple growth management strategies have been proposed to address the issue of sprawl, one of which is the greenbelt policy that dates back to the 1930s. However, the extent of the effectiveness of greenbelts has been unknown to date and is subject to controversy. Europe includes numerous cities with greenbelts, providing a sufficient sample of cities to statistically assess the effectiveness of the greenbelt strategy.

This study found that (1) greenbelts have been substantially effective in controlling urban sprawl and have led to decreases in the level of 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 more effective in cities in which the population size was greater. (4) The most important reason of why greenbelts were effective was a substantial reduction in land uptake per person as a result of densification of built-up areas.

According to the encouraging result of greenbelts in most of the European cities, we recommend the use of greenbelts as a tool in anti-sprawl strategies in other parts of the world where applicable. Moreover, 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.

Greenbelts should become an essential part of any de-sprawling strategy (Hennig et al., 2015) toward more compact green cities (Artmann et al., 2019). In this regard, Artmann et al. (2019) integrated the concepts of "smart growth" and "green infrastructure" and developed a structured conceptual framework for "smart-compact-green cities", in which greenbelts would fit properly. This framework was mainly proposed to address the danger of losing green spaces in compact cities as a result of densification which endangers provision of "urban ecosystem services" (Artmann et al., 2019). Hence, greenbelts not only help achieve more compact forms of urban development and limit urban sprawl, they also contribute to supply of an essential share of urban services.

Other types of urban growth strategies comparable to greenbelts include urban growth boundaries (UGB) and urban service boundaries (Bengston et al., 2004; Pendall et al., 2002). While a greenbelt designates a physical perpetual area, urban growth boundaries delineate a line surrounding the urban area and allocate separate zones to urban and rural areas. In contrast to greenbelts, they are wielded to contain the projected urban growth and is subject to amendment and expansion if necessary. Urban service boundaries, with even more flexibility, demonstrate the extent to which infrastructure and public services will be provided. Hence, development beyond the corresponding boundary will be restricted (Bengston et al., 2004). While greenbelts have been proven to be effective as a growth management strategy in restricting excessive urban development, further quantitative and qualitative research is required to provide an insightful understanding of the similarities, differences, and effectiveness of greenbelts in containment of urban sprawl compared to urban growth boundaries and urban service boundaries.

4. Overall Conclusion

Increasing awareness regarding urban sprawl and its negative consequences has brought great attention and concern to discovering and employing strategies to stop this unsustainable trend. While multiple growth management strategies have been proposed in this regard, their outcomes are still unknown due to the national or subnational nature of the studies and lack of proper international comparative evaluation, which makes the findings about their effectiveness highly "context-specific" (Hersperger et al., 2020).

This study focuses on greenbelts as a well-known growth management strategy and contains the analysis of temporal changes in urban sprawl in a 9-year timeframe, as well as two independent points in time, employing metrics of Weighted Urban Proliferation (*WUP*) and Weighted Sprawl per Capita (*WSPC*). The findings demonstrated significant success of greenbelts in limiting urban sprawl in European cities over time, and they are highly recommended as an anti-sprawl measure where applicable. In cities in which applying greenbelts is not feasible due to the existing distribution and spatial arrangement of built-up areas, the use of concepts similar to greenbelts, such as greenways or green wedges as urban development boundaries, with linear character, is advised, as done in the case of Leipzig.

To make a fair comparison, this study made an attempt to select non-coastal cities as much as possible (with or without greenbelts) since water acts as an obstacle to development and would prevent observing the actual development patterns. However, future studies could examine how well greenbelts work for coastal cities, how they would navigate urban development, and examine if they are reasonable and affordable policies to enforce while having a natural barrier.

While some countries provide explicit spatial planning frameworks and records, it is still unknown how many cities in Europe do or do not have greenbelts. Even by being conscious of the existence of greenbelt in certain cities, accessing information about it was challenging. Better and more detailed documentation of the cities with greenbelts and their associated information and data is suggested to ease the process of inspecting their effects on urban development. This would also help inform and monitor more cities for the impacts of greenbelts on urban sprawl.

While the cities with greenbelts clearly demonstrated strong decreases in urban sprawl compared to the cities without greenbelts, to observe the differences between these two groups in a particular year, future studies should bring together and compare more cities. With the evolution of data and availability of information, recent times should be subject to research to examine the extent of the contribution of greenbelts to more compact urban development patterns. Moreover, investigating the degree of reduction of urban sprawl in relation to the thickness of the greenbelts and the duration they have been in place would be a necessity in proper implementation of greenbelt strategies in the future.

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 of adequately taking advantage of such policies due to limited financial and administrative resources (Rudolf et al., 2018). While it is important to make use of growth management strategies such as greenbelts that have been proven to be effective, it is crucial to be realistic and consider the context of the target location as well, such as social, political, economic, and geographical situation, and their capacities in implementing certain strategies since not all measures necessarily comply with the circumstances of the context studied.

According to Hersperger et al. (2020), the most commonly used growth management approaches derived from 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 be effective in land preservation and curtailing urban sprawl if fully appreciated and correctly implemented, and if there is political will. In this regard, it would be helpful to examine the reasons of why some cities without greenbelts also 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.

Identifying case-specific drivers of urban sprawl would also help propose additional measures for each city. Densification, which is happening in the cities with greenbelts, should be practiced more rigorously, especially within the existing built-up areas, to alleviate the negative impacts that urban sprawl is imposing on the environment and on the future generations.

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6. Appendices

6.1 Appendix A: Changes in the boundaries of the cities

The boundaries of the reporting units were procured from Eurostat administrative units, *urban audit* data source corresponding to cities, greater cities and functional urban areas (European Commission - Eurostat, 2020c). These data cover all the cities in our analysis and are available for the reference years of 2001, 2004, 2014, 2018, and 2020, with some shapefiles missing in particular years. To ensure the accuracy of the analysis, we examined changes of the boundaries from 2004 to 2014, the closest years to the years studied, and changes from 2014 to 2020 to observe the most recent changes (Tab. 10). In cities in which the boundaries changed over time, we calculated the differences and included only the cities with less than 10% change in our study to ensure the accuracy of the analysis. Since the data for 2004 seemed to be less accurate, we mainly applied the shapefiles of 2014, expect a few cases for which we used the shapefiles of 2020 (i.e., Bordeaux, Bristol, Gyor, Linz, Lyon, Manchester, Marseille, Rennes, Stockholm, Tyneside, Valencia, and Vienna).

Table 10 Changes in the boundaries of the cities (Eurostat administrative units, urban audit).

Country	City	Changes in boundaries (Eurostat) 2004 - 2014	2014 - 2020
Austria	Linz	2.2%	
	Vienna		
Belgium	Antwerp		
	Bruges		
	Brussels (GC*)		
	Ghent		
Croatia	Osijek		
	Zagreb		
Denmark	Copenhagen		
France	Bordeaux	NA (2004 and 2014)	
	Lyon	NA (2004 and 2014)	
	Marseille	NA (2004 and 2014)	
	Rennes	NA (2004 and 2014)	
Germany	Berlin		
	Bonn		
	Cologne		
	Dortmund		
	Dusseldorf		
	Frankfurt		
	Hamburg	1.9%	-1.8%
	Hanover		
	Leipzig	-1.7%	
	Lubeck	8.6%	
	Munich		
	Munster		
	Nuremberg	1.4%	1.8%
	Stuttgart		
Hungary	Budapest		
	Gyor	-0.63	

Country	City	Changes in Boundaries (Eurostat) 2004 - 2014	2014 - 2020
Italy	Milan		
	Naples		
	Rome		
	Turin		
	Verona		
Norway	Oslo		
Poland	Krakow		
	Lodz		
	Warsaw		
Spain	Bilbao		
	Madrid		
	Seville	-1.42%	
	Valencia (GC)	NA (2004 and 2014)	
	Vitoria-Gasteiz		
	Zaragoza	-8.34%	
Sweden	Lund		
	Stockholm (GC)	1.7%	4.6%
	Uppsala		
UK	Bradford		
	Bristol		
	Cambridge	-2.04%	
	Coventry		
	Glasgow City		
	Manchester (GC)	NA (2004)	
	Leeds		
	Lincoln		
	Nottingham		-0.24%
	Oxford		
	Stoke-on-Trent		
	Tyneside (GC)	NA (2004)	
	York		

Legend	
No change	
Very small change	
Change	

* GC refers to Greater Cities.

6.2 Appendix B: Suitability comparison of available built-up areas datasets for cities in Europe

The dataset selection was made by scoring six potential data sources based on 8 mandatory or desirable suitability criteria and obtaining the highest total and mandatory scores (Tab. 11). In this comparison, the *High Resolution Layers (HRL) Imperviousness Density (IMD)* dataset, provided by the European Copernicus programme, gained a total score of 34 out of 40, covering 29 mandatory scores out of 30, and it was chosen as the best available data source for this context. These layers provide binary data presenting built-up and non-built-up areas, and their classification is based on imperviousness degree. The entities included in the built-up area classification in *HRL Imperviousness* dataset include (EEA, 2018):

- Housing areas (including scattered houses)
- Traffic areas (airports, harbours, railway yards, parking lots)
- Roads
- Railway tracks associated to other impervious surfaces (i.e. inside of built-up areas)
- Industrial, commercial areas, factories, energy production and distribution facilities
- Sealed surfaces, which are part of categories, such as allotment gardens, cemeteries, sport and recreation areas, camp sites, excluding green areas associated with them
- Artificial grass-covered sport pitches
- Construction sites with discernible evolving built-up structures.
- Single (farm) houses (where possible to identify from satellite imagery)
- Paved borders of water edges
- Greenhouses
- Permanent plastic covered soil
- Solar panel parks

Table 11 Suitability comparison of available built-up areas datasets for cities in Europe.

Data Source (DLR – Earth Observation Center, 2016; EEA, 2018; European Commission, 2016)	**Total score (out of 40)**	**Mandatory criteria score (out of 30)**	**Desirable criteria score (out of 10)**	**Data Suitability Criteria** 1. High resolution	2. Resolution consistent over time	3. Two points available in time	4. Contains "built-up areas" class, or it can be created by combining other classes	5. Class of "built-up areas" clear and can be selected consistently over time	6. Class of "built-up areas" consistent between countries	7. Distinguishes between "built-up areas" and "roads" (to remove the roads outside the boundary of cities)	8. Coverage of the intended countries
Importance	-	-	-	Mandatory	Mandatory	Desirable	Mandatory	Mandatory	Mandatory	Desirable	Mandatory
High Resolution Layers (HRL) Impervious-ness	**34**	29	5	20 m x 20 m (for status layers)	Consistent	4 points 2006 2009 2012 2015	Binary data presenting built-up and non-built-up areas, the classification is based on the imperviousness degree	The data have been modified for all time steps regarding the consistency of built-up areas	Classes are consistent throughout the final product	Roads are not distinguished	Covers all intended countries
Scores				*****	*****	*****	****	*****	*****	-	*****
Urban Atlas	**33**	24	9	50 m x 50 m (for class1)	Consistent	2 points 2006 2012	Providing land use map of urban areas, containing "Artificial Surfaces" (class 1) including Urban Fabric	Built-up areas can be identified and selected from multiple subclasses of class1 and are consistent in both time steps	Classes are consistent throughout the final product	Roads are distinguished in subclasses of class1	Doesn't cover Croatia, Norway, and certain cities within some countries
Scores				****	*****	****	*****	*****	*****	*****	-
Global Urban Footprint (GUF)	**25**	19	6	12 m x 12 m	No temporal data available reduced towards the poles in the only point in time	1 point For the reference year 2011, filling the gaps by the data of 2014	Containing 3 classes of urban areas, land surface and water	No temporal data available	Classes are consistent throughout the final product	The class of urban areas only present the vertical structures, meaning that roads are not included in it	Global coverage
Scores				*****	-	*	****	-	*****	*****	*****

Table 11 Continued

Data Source (European Environment Agency & European Topic Centre on Urban, Land and Soil Systems, 2017; European Commission, 2019)	**Total score (out of 40)**	**Mandatory criteria score (out of 30)**	**Desirable criteria score (out of 10)**	**Data Suitability Criteria** **1. High resolution**	**2. Resolution consistent over time**	**3. Two points available in time**	**4. Contains "built-up areas" class, or it can be created by combining other classes**	**5. Class of "built-up areas" clear and can be selected consistently over time**	**6. Class of "built-up areas" consistent between countries**	**7. Distinguishes between "built-up areas" and "roads" (to remove the roads outside the boundary of cities)**	**8. Coverage of the intended countries**
Importance	-	-	-	Mandatory	Mandatory	Desirable	Mandatory	Mandatory	Mandatory	Desirable	Mandatory
Corine Landcover	**34**	24	10	100 m x 100 m (for the first 4 time steps) 500 m x 500 m (for the last time step)	Consistent for the first 4 time steps out of 5	5 points 1990 2000 2006 2012 2018	Providing land use map of urban areas, containing "Artificial Surfaces" (class 1) including Urban Fabric	Built-up areas can be identified and selected from multiple subclasses of class1 and are consistent in all time steps	Classes are consistent throughout the final product	Roads are distinguished in subclasses of class1	Doesn't cover Norway, Sweden, and UK in the first time step Covers all intended countries in the last 4 time steps
Scores				*	****	*****	*****	*****	*****	*****	****
Global Human Settlement Layers (GHS-BUILT)	**33**	28	5	30 m x 30 m (for multi-temporal classification) 250 m x 250 m (for individual years)	Consistent	4 points 1975 1990 2000 2014 (1975 may not be so accurate and reliable)	Containing 4 classes of built-up areas presenting different time steps in multi-temporal classification	Built-up areas are available for different time steps consistently in a single map	Classes are consistent throughout the final product	Roads are not distinguished	Global coverage
Scores				*****	*****	*****	***	*****	*****	-	*****
GHS-BUILT (Sentinel-1)	**19**	18	1	20 m x 20 m	No temporal data available	1 point 2016	Binary data presenting built-up and non-built-up areas	No temporal data available	Classes are consistent throughout the final product	Roads are not distinguished	Global coverage
Scores				*****	-	*	***	-	*****	-	*****

6.3 Appendix C: Job data

Table 12 Part-time employment as a percentage of the total employment, average weekly hours of work (European Commission - Eurostat, 2020b), and conversion factors at the country level.

Country	2006				2015			
	Part-time employment/ Total employment (%)	Full-time hours of work	Part-time hours of work	Conversion factor (part-time into full-time equivalent)	Part-time employment/ Total employment (%)	Full-time hours of work	Part-time hours of work	Conversion factor (part-time into full-time equivalent)
Austria	22.2	44.1	20.5	0.46	27.7	42.9	20.5	0.48
Belgium	22.0	41.1	23.3	0.57	24.9	41.7	24.0	0.58
Croatia	6.6	42.0	21.5	0.51	5.9	41.1	18.7	0.45
Denmark	22.3	40.3	18.7	0.46	24.3	38.9	17.5	0.45
France	17.2	41.0	23.1	0.56	18.5	40.4	22.7	0.56
Germany	25.7	41.6	17.7	0.43	26.8	41.4	18.9	0.46
Hungary	3.7	40.9	23.3	0.57	6.1	40.9	22.6	0.55
Italy	13.3	41.0	21.2	0.52	18.2	40.5	20.8	0.51
Norway	28.4	39.3	19.2	0.49	26.1	39.0	18.8	0.48
Poland	9.4	42.5	21.9	0.52	7.1	42.1	21.9	0.52
Spain	12.1	42.1	19.0	0.45	16.2	41.4	18.7	0.45
Sweden	24.7	41.0	24.4	0.60	25	40.7	23.2	0.57
UK	24.2	42.9	18.7	0.44	25.3	42.8	19.2	0.45

Table 13 Total number of jobs, part-time jobs, full-time jobs, and full-time equivalents in the cities with greenbelts.

City	Country	2006					2015				
		Total Jobs	Part-time	Full-time	Full-time equivalent of part-time	Total full-time equivalent	Total Jobs	Part-time	Full-time	Full-time equivalent of part-time	Total full-time equivalent
Rome	IT	1,170,070	155,619	1,014,451	80,922	1,095,373	1,224,196	222,804	1,001,392	113,630	1,115,022
Manchester	UK	1,224,962	296,441	928,521	130,434	1,058,955	1,353,200	342,360	1,010,840	154,062	1,164,902
Vienna	AT	793,632	176,186	617,446	81,046	698,491	933,093	258,467	674,626	124,064	798,690
Budapest	HU	829,175	30,679	798,496	17,487	815,983	909,236	55,463	853,773	30,505	884,277
Stockholm	SE	735,593	181,691	553,902	109,015	662,916	870,625	217,656	652,969	124,064	777,033
Munich	DE	702,978	180,665	522,313	77,686	599,999	774,775	207,640	567,135	95,514	662,650
Brussels	BE	411,005	90,421	320,584	51,540	372,124	475,279	118,344	356,935	68,640	425,574
Cologne	DE	486,028	124,909	361,119	53,711	414,830	520,294	139,439	380,855	64,142	444,997
Tyneside	UK	414,271	100,254	314,017	44,112	358,129	426,000	107,778	318,222	48,500	366,722
Zagreb	HR	367,755	24,272	343,483	12,379	355,862	371,093	21,894	349,199	9,853	359,051
Leeds	UK	396,200	95,880	300,320	42,187	342,507	415,400	105,096	310,304	47,293	357,597
Krakow	PL	415,947	39,099	376,848	20,331	397,179	423,616	30,077	393,539	15,640	409,179
Frankfurt	DE	330,170	84,854	245,316	36,487	281,803	361,346	96,841	264,505	44,547	309,052
Oslo	NO	299,478	85,052	214,426	41,675	256,102	383,203	100,016	283,187	48,008	331,195
Stuttgart	DE	295,191	75,864	219,327	32,622	251,948	309,851	83,040	226,811	38,198	265,009
Dusseldorf	DE	294,615	75,716	218,899	32,558	251,457	295,546	79,206	216,340	36,435	252,775
Copenhagen	DK	279,296	62,283	217,013	28,650	245,663	331,095	80,456	250,639	36,205	286,844
Bradford	UK	222,500	53,845	168,655	23,692	192,347	247,000	62,491	184,509	28,121	212,630
Hanover	DE	255,973	65,785	190,188	28,288	218,476	267,062	71,573	195,489	32,923	228,413
Bristol	UK	215,300	52,103	163,197	22,925	186,123	249,400	63,098	186,302	28,394	214,696
Bilbao	ES	173,150	20,951	152,199	9,428	161,627	161,381	26,144	135,237	11,765	147,002
Coventry	UK	150,400	36,397	114,003	16,015	130,018	155,900	39,443	116,457	17,749	134,207
Nottingham	UK	140,300	33,953	106,347	14,939	121,287	153,900	38,937	114,963	17,522	132,485
Munster	DE	136,228	35,011	101,217	15,055	116,272	150,437	40,317	110,120	18,546	128,666
Stoke-on-Trent	UK	109,400	26,475	82,925	11,649	94,574	119,000	30,107	88,893	13,548	102,441
Vitoria-Gasteiz	ES	117,400	14,205	103,195	6,392	109,587	118,592	19,212	99,380	8,645	108,025
Rennes	FR	97,072	16,696	80,376	9,350	89,726	100,837	18,655	82,182	10,447	92,629
York	UK	101,750	24,624	77,127	10,834	87,961	111,000	28,083	82,917	12,637	95,554
Oxford	UK	88,867	21,506	67,361	9,463	76,824	101,300	25,629	75,671	11,533	87,204
Cambridge	UK	63,100	15,270	47,830	6,719	54,549	78,200	19,785	58,415	8,903	67,318

Table 14 Total number of jobs, part-time jobs, full-time jobs, and full-time equivalents in the cities without greenbelts.

City	Country	2006					2015				
		Total Jobs	Part-time	Full-time	Full-time equivalent of part-time	Total full-time equivalent	Total Jobs	Part-time	Full-time	Full-time equivalent of part-time	Total full-time equivalent
Berlin	DE	1,773,900	455,892	1,318,008	196,034	1,514,041	1,787,900	479,157	1,308,743	220,412	1,529,155
Madrid	ES	1,585,500	191,846	1,393,655	86,330	1,479,985	1,585,500	256,851	1,328,649	115,583	1,444,232
Hamburg	DE	905,500	232,714	672,787	100,067	772,853	934,100	250,339	683,761	115,156	798,917
Warsaw	PL	968,517	91,041	877,476	47,341	924,818	1,066,960	75,754	991,206	39,392	1,030,598
Valencia	ES	674,288	81,589	592,699	36,715	629,414	683,054	110,655	572,399	49,795	622,194
Milan	IT	624,749	83,092	541,657	43,208	584,865	589,294	107,252	482,042	54,698	536,741
Lyon	FR	472,906	81,340	391,566	45,550	437,116	522,965	96,749	426,216	54,179	480,396
Naples	IT	379,913	50,528	329,385	26,275	355,659	338,889	61,678	277,211	31,456	308,667
Turin	IT	367,036	48,816	318,220	25,384	343,604	408,734	74,390	334,344	37,939	372,283
Marseille	FR	439,309	75,561	363,748	42,314	406,062	384,163	71,070	313,093	39,799	352,892
Lodz	PL	413,577	38,876	374,700	20,216	394,916	400,087	28,406	371,681	14,771	386,452
Seville	ES	335,650	40,614	295,036	18,276	313,312	333,396	54,010	279,386	24,305	303,690
Zaragoza	ES	319,400	38,647	280,753	17,391	298,144	329,834	53,433	276,401	24,045	300,446
Bordeaux	FR	339,507	58,395	281,112	32,701	313,813	315,378	58,345	257,033	32,673	289,706
Glasgow	UK	269,000	65,098	203,902	28,643	232,545	302,800	76,608	226,192	34,474	260,665
Dortmund	DE	268,571	69,023	199,548	29,680	229,228	275,176	73,747	201,429	33,924	235,353
Leipzig	DE	256,213	65,847	190,366	28,314	218,680	279,850	75,000	204,850	34,500	239,350
Antwerp	BE	190,195	41,843	148,352	23,850	172,203	215,687	53,706	161,981	31,150	193,130
Nuremberg	DE	252,521	64,898	187,623	27,906	215,529	266,974	71,549	195,425	32,913	228,338
Bonn	DE	147,002	37,780	109,222	16,245	125,468	150,975	40,461	110,514	18,612	129,126
Verona	IT	113,824	15,139	98,685	7,872	106,557	114,693	20,874	93,819	10,646	104,465
Ghent	BE	107,226	23,590	83,636	13,446	97,082	118,502	29,507	88,995	17,114	106,109
Lubeck	DE	101,405	26,061	75,344	11,206	86,550	102,505	27,471	75,034	12,637	87,670
Uppsala	SE	93,186	23,017	70,169	13,810	83,979	106,422	26,606	79,817	15,165	94,982
Linz	AT	88,500	19,647	68,853	9,038	77,891	102,111	28,285	73,826	13,577	87,403
Gyor	HU	59,391	2,197	57,194	1,253	58,446	64,242	3,919	60,323	2,155	62,479
Bruges	BE	53,359	11,739	41,620	6,691	48,311	53,424	13,303	40,121	7,715	47,837
Lund	SE	50,132	12,383	37,749	7,430	45,179	52,441	13,110	39,331	7,473	46,804
Osijek	HR	54,136	3,573	50,563	1,822	52,385	45,330	2,674	42,656	1,204	43,859
Lincoln	UK	44,900	10,866	34,034	4,781	38,815	53,400	13,510	39,890	6,080	45,969

6.4 Appendix D: Metrics for measurement of urban sprawl

The weighted urban proliferation (*WUP*) metric developed by Schwick et al. (2012) was developed based on the method urban permeation (*UP*) by Jaeger et al. (2010b), which was previously proposed alongside two other metrics, sprawl per capita (*SPC*) and total sprawl (*TS*). Table 15 provides an overview of the metrics used for measurement of urban sprawl and their relationships.

Table 15 Metrics for measurement of urban sprawl and their associated equations.

Acronym	Name of the metric	Equation	Unit	Mathematical homogeneity
WUP	Weighted Urban Proliferation	$(PBA \cdot DIS) \cdot w_1(DIS) \cdot w_2(LUP)$	UPU per m^2 of landscape	Intensive
PBA	Percentage of Built-up Area	$A_{\text{built-up}}/A_{\text{reporting unit}}$	%	Intensive
DIS	Dispersion	–	UPU per m^2 of built-up area	Intensive
LUP	Land Uptake per Person (per inhabitant or job)	$A_{\text{built-up}}/N_{\text{inh+job}}$	m^2 per inhabitant or job	Intensive
UD	Utilization Density	$N_{\text{inh+job}}/A_{\text{built-up}}$	Inhabitants or jobs per km^2 of built-up area	Intensive
UP	Urban Permeation	$PBA \cdot DIS$	UPU per m^2 of landscape	Intensive
TS	Total Sprawl	$DIS \cdot A_{\text{built-up}}$	MUPU	Extensive
WTS	Weighted Total Sprawl	$w_1(DIS) \cdot w_2(LUP) \cdot TS$	MUPU	Extensive
SPC	Sprawl per Capita	$TS/N_{\text{inh+job}}$	UPU per inhabitant or job	Intensive
WSPC	Weighted Sprawl per Capita	$w_1(DIS) \cdot w_2(LUP) \cdot SPC$	UPU per inhabitant or job	Intensive

6.5 Appendix E: Values of metrics and their components in 2006 and 2015 and changes

Table 16 *WSPC*, *WUP*, and adjusted *WUP* in 2006 in the cities with greenbelts.

Population size category	City	Country	Population	Inhabitants and jobs	Built-up area (m^2)	City size (m^2)	Adjusted city size (m^2)	*WSPC* (UPU/inh or job)	*WUP* (UPU/m^2 of landscape)	Adjusted *WUP* (UPU/m^2 of landscape)
Very Large	Rome	IT	2547677	3643050	288080000	1283475965.9	1030610075.7	130.425	0.370	0.461
	Manchester	UK	2553700	3612655	422409200	1277325741.9	942606503.8	1842.773	5.212	7.063
Large	Vienna	AT	1652449	2350940	167116000	413266520.9	483847066.1	51.906	0.295	0.252
	Budapest	HU	1698106	2514089	210145600	525397207.8	472406508.1	212.395	1.016	1.130
	Stockholm	SE	1439402	2102318	181859200	1379706904.4	450552504.3	262.899	0.401	1.227
	Munich	DE	1259677	1859676	164861200	310933516.6	375485815.9	339.805	2.032	1.683
	Brussels	BE	1018804	1390928	92855200	162231468.6	319033746.5	28.390	0.243	0.124
	Cologne	DE	983347	1398177	157060800	407252951.3	287204155.9	1495.406	5.134	7.280
Medium-Large	Tyneside	UK	806623	1164752	161129200	406561780.9	249117327.4	3735.068	10.700	17.463
	Zagreb	HR	777633	1133495	109946000	640041251.0	241657176.0	620.089	1.098	2.909
	Leeds	UK	762500	1105007	142713600	551592092.2	236673656.2	2789.310	5.588	13.023
	Krakow	PL	756267	1153446	77689600	326874500.0	235523739.4	30.223	0.107	0.148
	Frankfurt	DE	651899	933702	103715600	248734159.4	228117023.4	1424.829	5.349	5.832
	Oslo	NO	538411	794513	67250000	453345358.0	217216846.3	234.896	0.412	0.859
	Stuttgart	DE	592569	844517	79190400	209806207.9	211924937.6	494.395	1.990	1.970
	Dusseldorf	DE	574514	825971	90510800	217452119.7	210754185.3	1325.633	5.035	5.195
	Copenhagen	DK	512486	758149	55476400	91073324.5	207652945.6	68.417	0.570	0.250
	Bradford	UK	491600	683947	82554800	367106717.6	199994689.5	2037.946	3.797	6.969
	Hanover	DE	515729	734205	95948400	204154285.5	199153144.5	3059.905	11.004	11.281
Medium	Bristol	UK	413600	599723	66976000	111446757.2	188605304.9	1489.934	8.018	4.738
	Bilbao	ES	354145	515772	13500800	41591007.7	175761141.3	0.000	0.000	0.000
	Coventry	UK	304800	434818	48348400	98740617.3	175302346.0	1449.542	6.383	3.595
	Nottingham	UK	289600	410887	47035600	74713253.0	172282767.7	1697.547	9.336	4.049
	Munster	DE	270868	387140	56546400	303678353.8	170554079.6	4119.087	5.251	9.350
	Stoke-on-Trent	UK	239500	334074	48714800	92629112.6	164591253.2	4524.856	16.319	9.184
	Vitoria-Gasteiz	ES	227568	337155	30062400	277141378.3	163738599.7	327.517	0.398	0.674
	Rennes	FR	200265	289991	29100800	50144036.7	160498605.7	797.446	4.612	1.441
	York	UK	189900	277861	38507200	271086205.6	159410525.0	3353.309	3.437	5.845
	Oxford	UK	145800	223424	19534000	45385933.7	154266257.6	278.864	1.373	0.404
	Cambridge	UK	112900	167449	15482400	40419642.8	151158350.5	440.068	1.823	0.487

Table 17 *LUP*, *PBA*, adjusted *PBA*, *DIS*, and the related metrics in 2006 in the cities with greenbelts.

City	Country	*LUP* (m^2/inh or job)	*PBA* (%)	Adjusted *PBA* (%)	*DIS* (UPU/m^2 of built-up)	*UD* (inh or job/km^2 of built-up)	$w_1(DIS)$	$w_2(LUP)$	*UP* (UPU/m^2 of landscape)	*TS* (MUPU)	*WTS* (MUPU)	*SPC* (UPU/inh or job)
Rome	IT	79.1	0.224	0.280	48.26	12646.0	1.278	0.027	10.83	13902948217.6	475145200.7	3816.3
Manchester	UK	116.9	0.331	0.448	48.45	8552.5	1.288	0.253	16.02	20466646592.1	6657304692.1	5665.3
Vienna	AT	71.1	0.404	0.345	48.98	14067.7	1.312	0.011	19.81	8184992407.6	122028938.6	3481.6
Budapest	HU	83.6	0.400	0.445	48.73	11963.6	1.301	0.040	19.49	10241296612.6	533980031.7	4073.6
Stockholm	SE	86.5	0.132	0.404	47.79	11560.1	1.253	0.051	6.30	8690722002.8	552698176.5	4133.9
Munich	DE	88.7	0.530	0.439	48.96	11280.3	1.312	0.060	25.96	8072161582.9	631926289.4	4340.6
Brussels	BE	66.8	0.572	0.291	49.22	14979.5	1.323	0.007	28.17	4570511226.0	39488499.4	3285.9
Cologne	DE	112.3	0.386	0.547	48.38	8902.1	1.284	0.214	18.66	7598194716.5	2090842075.4	5434.4
Tyneside	UK	138.3	0.396	0.647	48.48	7228.7	1.289	0.432	19.21	7810913600.8	4350428024.2	6706.1
Zagreb	HR	97.0	0.172	0.455	48.33	10309.6	1.282	0.103	8.30	5313730860.0	702868095.7	4687.9
Leeds	UK	129.2	0.259	0.603	47.95	7742.8	1.262	0.357	12.41	6842583371.1	3082207422.8	6192.3
Krakow	PL	67.4	0.238	0.330	48.72	14846.9	1.301	0.007	11.58	3785359723.8	34860283.2	3281.8
Frankfurt	DE	111.1	0.417	0.455	48.57	9002.5	1.294	0.204	20.25	5037953118.2	1330365689.8	5395.7
Oslo	NO	84.6	0.148	0.310	48.74	11814.3	1.301	0.044	7.23	3277713890.0	186627907.5	4125.4
Stuttgart	DE	93.8	0.377	0.374	48.41	10664.4	1.285	0.085	18.27	3833269912.9	417525150.0	4539.0
Dusseldorf	DE	109.6	0.416	0.429	48.61	9125.7	1.295	0.192	20.23	4399600557.6	1094934118.4	5326.6
Copenhagen	DK	73.2	0.609	0.267	49.06	13666.2	1.316	0.014	29.89	2721774260.6	51870382.8	3590.0
Bradford	UK	120.7	0.225	0.413	47.63	8284.8	1.244	0.285	10.71	3932253535.8	1393847187.0	5749.4
Hanover	DE	130.7	0.470	0.482	48.70	7652.1	1.300	0.370	22.89	4672969168.3	2246597814.2	6364.7
Bristol	UK	111.7	0.601	0.355	48.85	8954.3	1.307	0.209	29.36	3272029429.8	893547735.0	5455.9
Bilbao	ES	26.2	0.325	0.077	47.96	38203.1	1.262	0.000	15.57	647497963.0	0.0	1255.4
Coventry	UK	111.2	0.490	0.276	48.78	8993.4	1.303	0.205	23.89	2358460093.2	630286750.6	5424.0
Nottingham	UK	114.5	0.630	0.273	48.88	8735.7	1.308	0.232	30.77	2298907282.0	697499871.9	5595.0
Munster	DE	146.1	0.186	0.332	47.19	6846.4	1.219	0.490	8.79	2668316612.4	1594663159.0	6892.4
Stoke-on-Trent	UK	145.8	0.526	0.296	48.76	6857.8	1.302	0.489	25.64	2375403310.2	1511636744.7	7110.4
Vitoria-Gasteiz	ES	89.2	0.108	0.184	47.63	11215.2	1.245	0.062	5.17	1431976127.9	110423885.8	4247.2
Rennes	FR	100.4	0.580	0.181	48.86	9965.1	1.307	0.124	28.35	1421751594.9	231252219.3	4902.7
York	UK	138.6	0.142	0.242	46.75	7215.8	1.192	0.434	6.64	1800338288.7	931753923.7	6479.3
Oxford	UK	87.4	0.430	0.127	47.44	11437.7	1.234	0.054	20.42	926761915.0	62304973.0	4148.0
Cambridge	UK	92.5	0.383	0.102	48.12	10815.4	1.271	0.078	18.43	745013707.3	73688916.3	4449.2

Table 18 *WSPC*, *WUP*, and adjusted *WUP* in 2006 in the cities without greenbelts.

Population size category	City	Country	Population	Inhabitants and jobs	Built-up area (m^2)	City size (m^2)	Adjusted city size (m^2)	*WSPC* (UPU/inh or job)	*WUP* (UPU/m^2 of landscape)	Adjusted *WUP* (UPU/m^2 of landscape)
Very Large	Berlin	DE	3395189	4909230	425512000	891073204.5	1566152672.8	286.189	1.577	0.897
	Madrid	ES	3128600	4608585	178970000	603877865.2	1244988282.5	0.025	0.000	0.000
Large	Hamburg	DE	1743627	2516480	276918400	747130046.4	474120205.5	1363.477	4.592	7.237
	Warsaw	PL	1702139	2626957	170937600	516663316.0	467727921.1	21.091	0.107	0.118
	Valencia	ES	1359115	1988529	103970000	400301006.5	363670465.1	1.659	0.008	0.009
	Milan	IT	1308735	1893600	98743600	181742425.4	351961467.6	1.710	0.018	0.009
	Lyon	FR	965052	1402168	131171200	219778032.1	291176767.2	506.851	3.234	2.441
	Naples	IT	984242	1339901	69719600	118704752.7	273799906.8	1.628	0.018	0.008
Medium-Large	Turin	IT	900608	1244212	73527600	130647931.7	258594326.3	7.597	0.072	0.037
	Marseille	FR	870632	1276694	102942000	297147506.4	257990090.0	156.409	0.672	0.774
	Lodz	PL	760251	1155167	73803200	293077494.8	225233876.7	17.463	0.069	0.090
	Seville	ES	704414	1017726	55103200	141662833.0	224356632.1	2.614	0.019	0.012
	Zaragoza	ES	649181	947325	87044400	973312990.5	219859741.0	406.543	0.396	1.752
	Bordeaux	FR	560806	874619	127936800	245659589.0	215415584.7	4643.398	16.532	18.853
	Glasgow	UK	580700	813245	101262800	175538764.6	210527561.4	2575.357	11.931	9.948
	Dortmund	DE	588168	817396	103515600	279379627.1	207240840.0	2671.678	7.817	10.538
	Leipzig	DE	502651	721331	108544000	298505286.9	202079201.0	4882.055	11.797	17.427
	Antwerp	BE	461496	633699	103659200	202747750.3	198034233.6	6200.026	19.378	19.840
	Nuremberg	DE	499237	714766	83069200	184036501.0	196031511.3	1791.761	6.959	6.533
Medium	Bonn	DE	312818	438286	46766400	142336348.5	171966254.4	1128.894	3.476	2.877
	Verona	IT	259380	365937	44960400	198723837.6	165606736.9	2291.548	4.220	5.064
	Ghent	BE	233120	330202	60656000	157003549.7	164888305.9	8056.723	16.944	16.134
	Lubeck	DE	211825	298375	52443200	212814700.8	160392360.9	7081.607	9.929	13.174
	Uppsala	SE	185187	269166	35873600	2249339488.5	159863869.2	2752.835	0.329	4.635
	Linz	AT	187936	265827	41202400	95100707.4	158351655.5	5332.892	14.907	8.952
	Gyor	HU	128265	186711	29104800	174501959.6	151122485.6	5126.280	5.485	6.333
	Bruges	BE	117224	165535	36705200	139214291.3	149959450.4	10739.394	12.770	11.855
	Lund	SE	104173	149352	19665600	443053016.8	149408639.8	2665.565	0.899	2.665
	Osijek	HR	110297	162682	18955600	174971223.9	148733719.9	1442.467	1.341	1.578
	Lincoln	UK	88100	126915	16776000	35615048.1	147698721.5	2983.712	10.632	2.564

Table 19 *LUP*, *PBA*, adjusted *PBA*, *DIS*, and the related metrics in 2006 in the cities without greenbelts.

City	Country	***LUP*** (m^2/inh or job)	***PBA*** (%)	**Adjusted *PBA*** (%)	***DIS*** (UPU/m^2 of built-up)	***UD*** (inh or job/km^2 of built-up)	$w_1(DIS)$	$w_2(LUP)$	***UP*** (UPU/m^2 of landscape)	***TS*** (MUPU)	***WTS*** (MUPU)	***SPC*** (UPU/inh or job)
Berlin	DE	86.7	0.478	0.272	48.96	11537.2	1.311	0.051	23.38	20831225053.0	1404968264.7	4243.3
Madrid	ES	38.8	0.296	0.144	48.84	25750.6	1.306	0.000	14.47	8740903748.5	114167.6	1896.7
Hamburg	DE	110.0	0.371	0.584	48.70	9087.4	1.299	0.196	18.05	13484973480.7	3431161778.5	5358.7
Warsaw	PL	65.1	0.331	0.365	48.60	15367.9	1.295	0.005	16.08	8307958807.1	55406142.8	3162.6
Valencia	ES	52.3	0.260	0.286	48.09	19126.0	1.269	0.001	12.49	4999572119.6	3299377.6	2514.2
Milan	IT	52.1	0.543	0.281	49.36	19176.9	1.329	0.001	26.82	4874031492.9	3238696.4	2573.9
Lyon	FR	93.5	0.597	0.450	49.14	10689.6	1.320	0.084	29.33	6445927225.7	710690878.3	4597.1
Naples	IT	52.0	0.587	0.255	48.86	19218.4	1.307	0.000	28.70	3406395773.8	2181524.7	2542.3
Turin	IT	59.1	0.563	0.284	49.07	16921.7	1.317	0.002	27.62	3608066242.1	9452825.4	2899.9
Marseille	FR	80.6	0.346	0.399	48.55	12402.1	1.292	0.031	16.82	4997497479.7	199686494.1	3914.4
Lodz	PL	63.9	0.252	0.328	48.65	15652.0	1.297	0.004	12.25	3590826797.1	20172805.0	3108.5
Seville	ES	54.1	0.389	0.246	48.53	18469.5	1.292	0.001	18.88	2674423893.4	2660006.1	2627.8
Zaragoza	ES	91.9	0.089	0.396	47.58	10883.2	1.242	0.075	4.26	4141549050.0	385128220.7	4371.8
Bordeaux	FR	146.3	0.521	0.594	49.05	6836.3	1.316	0.492	25.55	6275536723.1	4061203802.4	7175.2
Glasgow	UK	124.5	0.577	0.481	49.22	8031.0	1.323	0.318	28.40	4984490195.9	2094396496.8	6129.1
Dortmund	DE	126.6	0.371	0.499	48.58	7896.4	1.294	0.336	18.00	5028349977.0	2183818996.2	6151.7
Leipzig	DE	150.5	0.364	0.537	48.42	6645.5	1.286	0.521	17.61	5255337943.0	3521577513.0	7285.6
Antwerp	BE	163.6	0.511	0.523	48.63	6113.3	1.296	0.601	24.86	5040895066.4	3928950300.9	7954.7
Nuremberg	DE	116.2	0.451	0.424	48.48	8604.5	1.289	0.247	21.88	4027572780.9	1280690090.0	5634.8
Bonn	DE	106.7	0.329	0.272	48.43	9371.8	1.287	0.170	15.91	2264931826.8	494778466.2	5167.7
Verona	IT	122.9	0.226	0.271	48.21	8139.1	1.275	0.303	10.91	2167405103.6	838562233.5	5922.9
Ghent	BE	183.7	0.386	0.368	48.66	5443.8	1.298	0.695	18.80	2951607091.5	2660346009.6	8938.8
Lubeck	DE	175.8	0.246	0.327	48.05	5689.5	1.267	0.662	11.84	2519996450.9	2112974534.9	8445.7
Uppsala	SE	133.3	0.016	0.224	46.04	7503.2	1.146	0.391	0.73	1651770495.6	740969521.9	6136.6
Linz	AT	155.0	0.433	0.260	48.48	6451.7	1.289	0.551	21.00	1997393466.2	1417626626.2	7513.9
Gyor	HU	155.9	0.167	0.193	47.59	6415.1	1.242	0.556	7.94	1385196097.3	957132856.4	7418.9
Bruges	BE	221.7	0.264	0.245	47.94	4509.9	1.261	0.801	12.64	1759464863.2	1777745539.1	10629.0
Lund	SE	131.7	0.044	0.132	46.22	7594.6	1.158	0.378	2.05	909039803.5	398107474.1	6086.6
Osijek	HR	116.5	0.108	0.127	45.32	8582.3	1.096	0.249	4.91	859131672.4	234663357.3	5281.0
Lincoln	UK	132.2	0.471	0.114	47.57	7565.3	1.241	0.382	22.41	798025764.2	378677816.9	6287.9

Table 20 *WSPC*, *WUP*, and adjusted *WUP* in 2015 in the cities with greenbelts.

Population size category	City	Country	Population	Inhabitants and jobs	Built-up area (m^2)	City size (m^2)	Adjusted city size (m^2)	*WSPC* (UPU/inh or job)	*WUP* (UPU/m^2 of landscape)	Adjusted *WUP* (UPU/m^2 of landscape)
Very Large	Rome	IT	2872021	3987043	294462800	1283475965.9	1030610075.7	71.304	0.222	0.276
	Manchester	UK	2744508	3909410	433911600	1277325741.9	942606503.8	1411.741	4.321	5.855
Large	Vienna	AT	1791803	2590493	169934400	413266520.9	483847066.1	23.424	0.147	0.125
	Budapest	HU	1757618	2641895	214447600	525397207.8	472406508.1	167.541	0.842	0.937
	Stockholm	SE	1689952	2466985	186888800	1379706904.4	450552504.3	87.084	0.156	0.477
	Munich	DE	1429584	2092234	167730000	310933516.6	375485815.9	152.650	1.027	0.851
	Brussels	BE	1196831	1622405	93249200	162231468.6	319033746.5	5.578	0.056	0.028
	Cologne	DE	1046680	1491677	159473200	407252951.3	287204155.9	1139.120	4.172	5.916
Medium-Large	Tyneside	UK	843434	1210156	165243600	406561780.9	249117327.4	3571.602	10.631	17.350
	Zagreb	HR	799999	1159050	111242000	640041251.0	241657176.0	578.318	1.047	2.774
	Leeds	UK	770230	1127827	143668800	551592092.2	236673656.2	2638.235	5.394	12.572
	Krakow	PL	763272	1172451	85839600	326874500.0	235523739.4	67.836	0.243	0.338
	Frankfurt	DE	717624	1026676	105904000	248734159.4	228117023.4	932.260	3.848	4.196
	Oslo	NO	647676	978871	67434000	453345358.0	217216846.3	37.802	0.082	0.170
	Stuttgart	DE	612441	877450	80437600	209806207.9	211924937.6	421.719	1.764	1.746
	Dusseldorf	DE	604527	857302	91694000	217452119.7	210754185.3	1157.376	4.563	4.708
	Copenhagen	DK	583349	870193	56488800	91073324.5	207652945.6	21.119	0.202	0.088
	Bradford	UK	529666	742296	83819200	367106717.6	199994689.5	1467.925	2.968	5.448
	Hanover	DE	523642	752055	96800800	204154285.5	199153144.5	2879.930	10.609	10.875
Medium	Bristol	UK	445901	660597	67439200	111446757.2	188605304.9	888.288	5.265	3.111
	Bilbao	ES	345141	492143	13503600	41591007.7	175761141.3	0.000	0.000	0.000
	Coventry	UK	341407	475614	48382800	98740617.3	175302346.0	865.108	4.167	2.347
	Nottingham	UK	316585	449070	47052000	74713253.0	172282767.7	1040.956	6.257	2.713
	Munster	DE	302178	430844	57992400	303678353.8	170554079.6	3120.520	4.427	7.883
	Stoke-on-Trent	UK	251338	353779	48840400	92629112.6	164591253.2	3769.519	14.397	8.102
	Vitoria-Gasteiz	ES	243918	351943	32031200	277141378.3	163738599.7	385.148	0.489	0.828
	Rennes	FR	215366	307995	30031600	50144036.7	160498605.7	663.658	4.076	1.274
	York	UK	205648	301202	39185600	271086205.6	159410525.0	2654.316	2.949	5.015
	Oxford	UK	158786	245990	19544800	45385933.7	154266257.6	128.898	0.699	0.206
	Cambridge	UK	129711	197029	15482400	40419642.8	151158350.5	122.488	0.597	0.160

Table 21 *LUP*, *PBA*, adjusted *PBA*, *DIS*, and the related metrics in 2015 in the cities with greenbelts.

City	Country	*LUP* (m^2/inh or job)	*PBA* (%)	Adjusted *PBA* (%)	*DIS* (UPU/m^2 of built-up)	*UD* (inh or job/km^2 of built-up)	w_1(*DIS*)	w_2(*LUP*)	*UP* (UPU/m^2 of landscape)	*TS* (MUPU)	*WTS* (MUPU)	*SPC* (UPU/inh or job)
Rome	IT	73.9	0.229	0.286	48.28	13540.1	1.279	0.016	11.08	14217971398.8	284290419.6	3566.0
Manchester	UK	111.0	0.340	0.460	48.49	9009.7	1.290	0.203	16.47	21040269345.2	5519074945.6	5382.0
Vienna	AT	65.6	0.411	0.351	48.99	15244.1	1.313	0.006	20.15	8325935928.0	60679737.4	3214.0
Budapest	HU	81.2	0.408	0.454	48.78	12319.5	1.303	0.032	19.91	10460121307.6	442625821.8	3959.3
Stockholm	SE	75.8	0.135	0.415	47.80	13200.3	1.254	0.019	6.47	8933454708.8	214834109.4	3621.2
Munich	DE	80.2	0.539	0.447	48.97	12473.8	1.312	0.030	26.42	8214348637.2	319380301.1	3926.1
Brussels	BE	57.5	0.575	0.292	49.22	17398.6	1.323	0.001	28.29	4590155502.8	9049940.5	2829.2
Cologne	DE	106.9	0.392	0.555	48.40	9353.8	1.285	0.171	18.95	7717721461.3	1699198916.8	5173.9
Tyneside	UK	136.5	0.406	0.663	48.51	7323.5	1.290	0.418	19.71	8015178824.0	4322195315.2	6623.3
Zagreb	HR	96.0	0.174	0.460	48.35	10419.2	1.283	0.097	8.40	5378866627.3	670299403.2	4640.8
Leeds	UK	127.4	0.260	0.607	47.96	7850.2	1.262	0.342	12.49	6890469146.4	2975473001.2	6109.5
Krakow	PL	73.2	0.263	0.364	48.81	13658.6	1.305	0.015	12.82	4189719284.5	79534444.6	3573.5
Frankfurt	DE	103.2	0.426	0.464	48.59	9694.4	1.294	0.144	20.69	5145869005.8	957129226.8	5012.2
Oslo	NO	68.9	0.149	0.310	48.74	14516.0	1.302	0.009	7.25	3286779015.1	37003044.6	3357.7
Stuttgart	DE	91.7	0.383	0.380	48.43	10908.5	1.287	0.074	18.57	3895614686.2	370037432.4	4439.7
Dusseldorf	DE	107.0	0.422	0.435	48.62	9349.6	1.296	0.172	20.50	4458504298.6	992220895.9	5200.6
Copenhagen	DK	64.9	0.620	0.272	49.06	15404.7	1.316	0.005	30.43	2771069381.8	18377271.0	3184.4
Bradford	UK	112.9	0.228	0.419	47.64	8855.9	1.245	0.219	10.88	3993555725.7	1089634587.2	5380.0
Hanover	DE	128.7	0.474	0.486	48.71	7769.1	1.300	0.353	23.10	4715100175.4	2165865547.8	6269.6
Bristol	UK	102.1	0.605	0.358	48.86	9795.4	1.307	0.136	29.57	3295071893.7	586800242.1	4988.0
Bilbao	ES	27.4	0.325	0.077	47.96	36445.3	1.262	0.000	15.57	647646564.7	0.0	1316.0
Coventry	UK	101.7	0.490	0.276	48.78	9830.2	1.303	0.134	23.90	2360121209.1	411457474.6	4962.3
Nottingham	UK	104.8	0.630	0.273	48.88	9544.1	1.308	0.155	30.78	2299773308.0	467462255.0	5121.2
Munster	DE	134.6	0.191	0.340	47.22	7429.3	1.221	0.402	9.02	2738278184.1	1344457210.9	6355.6
Stoke-on-Trent	UK	138.1	0.527	0.297	48.76	7243.6	1.303	0.430	25.71	2381548258.7	1333576702.5	6731.7
Vitoria-Gasteiz	ES	91.0	0.116	0.196	47.80	10987.5	1.254	0.071	5.53	1531247031.6	135550096.5	4350.8
Rennes	FR	97.5	0.599	0.187	48.91	10255.7	1.309	0.106	29.29	1468705008.1	204403417.1	4768.6
York	UK	130.1	0.145	0.246	46.79	7686.5	1.195	0.365	6.76	1833548692.0	799485268.1	6087.4
Oxford	UK	79.5	0.431	0.127	47.45	12586.0	1.234	0.028	20.43	927327076.1	31707610.1	3769.8
Cambridge	UK	78.6	0.383	0.102	48.12	12726.0	1.271	0.025	18.43	745013707.3	24133759.2	3781.2

Table 22 *WSPC*, *WUP*, and adjusted *WUP* in 2015 in the cities without greenbelts.

Population size category	City	Country	Population	Inhabitants and jobs	Built-up area (m^2)	City size (m^2)	Adjusted city size (m^2)	*WSPC* (UPU/inh or job)	*WUP* (UPU/m^2 of landscape)	Adjusted *WUP* (UPU/m^2 of landscape)
Very Large	Berlin	DE	3469849	4999004	430930800	891073204.5	1566152672.8	274.532	1.540	0.876
	Madrid	ES	3141991	4586223	198177600	603877865.2	1244988282.5	0.111	0.001	0.000
Large	Hamburg	DE	1762791	2561708	283387200	747130046.4	474120205.5	1404.798	4.817	7.590
	Warsaw	PL	1743399	2773997	185547200	516663316.0	467727921.1	28.013	0.150	0.166
	Valencia	ES	1383908	2006102	106927600	400301006.5	363670465.1	2.118	0.011	0.012
	Milan	IT	1337155	1873896	99447200	181742425.4	351961467.6	2.124	0.022	0.011
	Lyon	FR	1066305	1546701	133645600	219778032.1	291176767.2	282.483	1.988	1.501
	Naples	IT	978399	1287066	69962400	118704752.7	273799906.8	2.812	0.030	0.013
Medium-Large	Turin	IT	896773	1269056	73774800	130647931.7	258594326.3	6.312	0.061	0.031
	Marseille	FR	893431	1246323	104728400	297147506.4	257990090.0	219.463	0.920	1.060
	Lodz	PL	699453	1085905	76730000	293077494.8	225233876.7	48.225	0.179	0.233
	Seville	ES	693878	997568	56720000	141662833.0	224356632.1	4.752	0.033	0.021
	Zaragoza	ES	664953	965399	90728800	973312990.5	219859741.0	480.101	0.476	2.108
	Bordeaux	FR	635780	925486	132976400	245659589.0	215415584.7	4390.760	16.541	18.864
	Glasgow	UK	602990	863655	104282000	175538764.6	210527561.4	2244.928	11.045	9.209
	Dortmund	DE	580511	815864	105065600	279379627.1	207240840.0	2868.913	8.378	11.294
	Leipzig	DE	544479	783829	110053200	298505286.9	202079201.0	3918.174	10.289	15.198
	Antwerp	BE	515593	708723	104587200	202747750.3	198034233.6	4663.543	16.302	16.690
	Nuremberg	DE	501072	729410	83673600	184036501.0	196031511.3	1678.303	6.652	6.245
Medium	Bonn	DE	313958	443084	48391600	142336348.5	171966254.4	1289.708	4.015	3.323
	Verona	IT	260125	364590	46198400	198723837.6	165606736.9	2626.988	4.820	5.783
	Ghent	BE	253914	360023	63554000	157003549.7	164888305.9	7429.244	17.036	16.221
	Lubeck	DE	214420	302090	53248000	212814700.8	160392360.9	7131.508	10.123	13.432
	Uppsala	SE	209705	304687	37863200	2249339488.5	159863869.2	2075.768	0.281	3.956
	Linz	AT	196127	283530	41603200	95100707.4	158351655.5	4540.627	13.537	8.130
	Gyor	HU	129372	191851	32506400	174501959.6	151122485.6	6394.438	7.030	8.118
	Bruges	BE	118335	166172	38904000	139214291.3	149959450.4	11654.687	13.911	12.915
	Lund	SE	113078	159882	20604800	443053016.8	149408639.8	2448.285	0.883	2.620
	Osijek	HR	106610	150469	19410000	174971223.9	148733719.9	2303.088	1.981	2.330
	Lincoln	UK	96634	142603	16809600	35615048.1	147698721.5	1814.049	7.263	1.751

Table 23 *LUP*, *PBA*, adjusted *PBA*, *DIS*, and the related metrics in 2015 in the cities without greenbelts.

City	Country	***LUP*** (m^2/inh or job)	***PBA*** (%)	**Adjusted *PBA*** (%)	***DIS*** (UPU/m^2 of built-up)	***UD*** (inh or job/km^2 of built-up)	w_1(*DIS*)	w_2(*LUP*)	***UP*** (UPU/m^2 of landscape)	***TS*** (MUPU)	***WTS*** (MUPU)	***SPC*** (UPU/inh or job)
Berlin	DE	86.2	0.484	0.275	48.97	11600.5	1.312	0.050	23.68	21102198633.5	1372388753.6	4221.3
Madrid	ES	43.2	0.328	0.159	48.93	23142.0	1.310	0.000	16.06	9697277849.4	508269.2	2114.4
Hamburg	DE	110.6	0.379	0.598	48.72	9039.6	1.300	0.200	18.48	13805505004.6	3598683275.7	5389.2
Warsaw	PL	66.9	0.359	0.397	48.64	14950.4	1.297	0.007	17.47	9024887780.4	77706875.7	3253.4
Valencia	ES	53.3	0.267	0.294	48.12	18761.3	1.271	0.001	12.85	5144866383.6	4249093.7	2564.6
Milan	IT	53.1	0.547	0.283	49.37	18843.1	1.329	0.001	27.01	4909573015.8	3981040.2	2620.0
Lyon	FR	86.4	0.608	0.459	49.16	11573.2	1.320	0.050	29.89	6570190098.8	436916829.5	4247.9
Naples	IT	54.4	0.589	0.256	48.86	18396.5	1.307	0.001	28.80	3418594439.5	3619717.2	2656.1
Turin	IT	58.1	0.565	0.285	49.08	17201.8	1.317	0.002	27.71	3620679796.0	8009876.4	2853.0
Marseille	FR	84.0	0.352	0.406	48.56	11900.5	1.293	0.042	17.12	5085974511.5	273521741.5	4080.8
Lodz	PL	70.7	0.262	0.341	48.69	14152.3	1.299	0.011	12.75	3735931523.6	52367631.9	3440.4
Seville	ES	56.9	0.400	0.253	48.58	17587.6	1.294	0.001	19.45	2755177970.4	4740433.9	2761.9
Zaragoza	ES	94.0	0.093	0.413	47.69	10640.5	1.247	0.086	4.45	4326408271.7	463488755.0	4481.5
Bordeaux	FR	143.7	0.541	0.617	49.07	6959.8	1.317	0.473	26.56	6525525611.7	4063586803.0	7050.9
Glasgow	UK	120.7	0.594	0.495	49.24	8281.9	1.324	0.285	29.25	5134996888.9	1938843618.9	5945.7
Dortmund	DE	128.8	0.376	0.507	48.61	7765.3	1.295	0.354	18.28	5106973000.0	2340643240.4	6259.6
Leipzig	DE	140.4	0.369	0.545	48.42	7122.3	1.286	0.448	17.85	5328436980.1	3071178196.9	6798.0
Antwerp	BE	147.6	0.516	0.528	48.64	6776.4	1.297	0.501	25.09	5087040875.9	3305160113.3	7177.8
Nuremberg	DE	114.7	0.455	0.427	48.49	8717.3	1.289	0.234	22.05	4057140414.7	1224171095.8	5562.2
Bonn	DE	109.2	0.340	0.281	48.45	9156.2	1.288	0.189	16.47	2344786910.9	571449126.0	5292.0
Verona	IT	126.7	0.232	0.279	48.25	7891.8	1.278	0.336	11.22	2229051086.8	957773574.0	6113.9
Ghent	BE	176.5	0.405	0.385	48.70	5664.8	1.300	0.665	19.71	3094952692.0	2674698769.6	8596.5
Lubeck	DE	176.3	0.250	0.332	48.06	5673.3	1.268	0.664	12.03	2559365120.0	2154357271.2	8472.2
Uppsala	SE	124.3	0.017	0.237	46.09	8047.0	1.149	0.315	0.78	1745017579.6	632459644.3	5727.2
Linz	AT	146.7	0.437	0.263	48.48	6815.1	1.289	0.495	21.21	2017008006.5	1287403860.3	7113.9
Gyor	HU	169.4	0.186	0.215	47.75	5901.9	1.251	0.632	8.89	1552075604.3	1226779361.0	8090.0
Bruges	BE	234.1	0.279	0.259	47.94	4271.3	1.261	0.823	13.40	1864878801.6	1936682675.8	11222.6
Lund	SE	128.9	0.047	0.138	46.23	7759.5	1.159	0.355	2.15	952582363.2	391436676.1	5958.0
Osijek	HR	129.0	0.111	0.131	45.44	7752.1	1.105	0.356	5.04	882014468.4	346543356.2	5861.8
Lincoln	UK	117.9	0.472	0.114	47.57	8483.4	1.241	0.261	22.45	799628805.8	258688775.5	5607.4

Table 24 Absolute and relative changes in *WSPC*, *WUP*, and their components between 2006 and 2015 in the cities with greenbelts.

City	Country	***WSPC* Absolute Changes** (UPU/inh or job)	***WSPC* Relative Changes** (%)	***WUP* Absolute Changes** (UPU/ m^2 of landscape)	***WUP* Relative Changes** (%)	***LUP* Absolute Changes** (m^2/inh or job)	***LUP* Relative Changes** (%)	***PBA* Absolute Changes** (Percentage Point)	***PBA* Relative Changes** (%)	***DIS* Absolute Changes** (UPU/m^2 of built-up)	***DIS* Relative Changes** (%)
Rome	IT	-59.12	-45.33	-0.15	-40.16	-5.20	-6.57	0.50	2.22	0.024	0.049
Manchester	UK	-431.03	-23.39	-0.89	-17.10	-5.90	-5.05	0.90	2.72	0.038	0.078
Vienna	AT	-28.48	-54.87	-0.15	-50.23	-5.50	-7.74	0.68	1.69	0.017	0.035
Budapest	HU	-44.85	-21.12	-0.17	-17.11	-2.40	-2.87	0.82	2.05	0.043	0.088
Stockholm	SE	-175.82	-66.88	-0.24	-61.13	-10.70	-12.37	0.36	2.77	0.013	0.027
Munich	DE	-187.15	-55.08	-1.01	-49.46	-8.50	-9.58	0.92	1.74	0.010	0.021
Brussels	BE	-22.81	-80.35	-0.19	-77.09	-9.30	-13.92	0.24	0.42	0.003	0.005
Cologne	DE	-356.29	-23.83	-0.96	-18.73	-5.40	-4.81	0.59	1.54	0.018	0.037
Tyneside	UK	-163.47	-4.38	-0.07	-0.65	-1.80	-1.30	1.01	2.55	0.029	0.060
Zagreb	HR	-41.77	-6.74	-0.05	-4.63	-1.00	-1.03	0.20	1.18	0.022	0.046
Leeds	UK	-151.08	-5.42	-0.19	-3.46	-1.80	-1.39	0.17	0.67	0.015	0.030
Krakow	PL	37.61	124.45	0.14	128.32	5.80	8.61	2.49	10.49	0.085	0.174
Frankfurt	DE	-492.57	-34.57	-1.50	-28.06	-7.90	-7.11	0.88	2.11	0.015	0.031
Oslo	NO	-197.09	-83.91	-0.33	-80.16	-15.70	-18.56	0.04	0.28	0.001	0.003
Stuttgart	DE	-72.68	-14.70	-0.23	-11.37	-2.10	-2.24	0.59	1.57	0.025	0.051
Dusseldorf	DE	-168.26	-12.69	-0.47	-9.38	-2.60	-2.37	0.54	1.31	0.015	0.031
Copenhagen	DK	-47.30	-69.13	-0.37	-64.61	-8.30	-11.34	1.11	1.83	-0.007	-0.014
Bradford	UK	-570.02	-27.97	-0.83	-21.82	-7.80	-6.46	0.34	1.53	0.013	0.027
Hanover	DE	-179.98	-5.88	-0.40	-3.59	-2.00	-1.53	0.42	0.89	0.006	0.013
Bristol	UK	-601.65	-40.38	-2.75	-34.33	-9.60	-8.59	0.41	0.69	0.006	0.013
Bilbao	ES	0.00	0.00	0.00	0.00	1.20	4.58	0.01	0.02	0.001	0.002
Coventry	UK	-584.43	-40.32	-2.22	-34.72	-9.50	-8.54	0.04	0.07	0.000	-0.001
Nottingham	UK	-656.59	-38.68	-3.08	-32.98	-9.70	-8.47	0.02	0.03	0.001	0.003
Munster	DE	-998.57	-24.24	-0.82	-15.69	-11.50	-7.87	0.48	2.56	0.030	0.063
Stoke-on-Trent	UK	-755.34	-16.69	-1.92	-11.78	-7.70	-5.28	0.14	0.26	0.000	0.001
Vitoria-Gasteiz	ES	57.63	17.60	0.09	22.75	1.80	2.02	0.71	6.55	0.171	0.360
Rennes	FR	-133.79	-16.78	-0.54	-11.61	-2.90	-2.89	0.02	3.20	0.049	0.101
York	UK	-698.99	-20.84	-0.49	-14.20	-8.50	-6.13	0.25	1.76	0.038	0.081
Oxford	UK	-149.97	-53.78	-0.67	-49.10	-7.90	-9.04	0.02	0.06	0.003	0.006
Cambridge	UK	-317.58	-72.17	-1.23	-67.25	-13.90	-15.03	0.00	0.00	0.000	0.000

Table 25 Absolute and relative changes in *WSPC*, *WUP*, and their components between 2006 and 2015 in the cities without greenbelts.

City	Country	*WSPC* Absolute Changes (UPU/inh or job)	*WSPC* Relative Changes (%)	*WUP* Absolute Changes (UPU/ m^2 of landscape)	*WUP* Relative Changes (%)	*LUP* Absolute Changes (m^2/inh or job)	*LUP* Relative Changes (%)	*PBA* Absolute Changes (Percentage Point)	*PBA* Relative Changes (%)	*DIS* Absolute Changes (UPU/m^2 of built-up)	*DIS* Relative Changes (%)
Berlin	DE	-11.66	-4.07	-0.04	-2.32	-0.50	-0.58	0.61	1.27	0.013	0.027
Madrid	ES	0.09	347.37	0.00	447.06	4.40	11.34	3.18	10.73	0.092	0.189
Hamburg	DE	41.32	3.03	0.22	4.89	0.60	0.55	0.87	2.34	0.019	0.040
Warsaw	PL	6.92	32.82	0.04	40.31	1.80	2.76	2.83	8.55	0.037	0.076
Valencia	ES	0.46	27.66	0.00	28.82	1.00	1.91	0.74	2.85	0.029	0.060
Milan	IT	0.41	24.21	0.00	23.59	1.00	1.92	0.39	0.71	0.008	0.017
Lyon	FR	-224.37	-44.27	-1.25	-38.52	-7.10	-7.59	0.01	1.89	0.020	0.041
Naples	IT	1.18	72.74	0.01	66.08	2.40	4.62	0.20	0.35	0.005	0.010
Turin	IT	-1.29	-16.92	-0.01	-15.44	-1.00	-1.69	0.19	0.34	0.007	0.013
Marseille	FR	63.05	40.31	0.25	36.98	3.40	4.22	0.01	1.74	0.017	0.034
Lodz	PL	30.76	176.15	0.11	159.56	6.80	10.64	1.00	3.97	0.035	0.072
Seville	ES	2.14	81.81	0.01	77.07	2.80	5.18	1.14	2.94	0.040	0.083
Zaragoza	ES	73.56	18.09	0.08	20.35	2.10	2.29	0.38	4.24	0.105	0.221
Bordeaux	FR	-252.64	-5.44	0.01	0.06	-2.60	-1.78	0.02	3.94	0.021	0.043
Glasgow	UK	-330.43	-12.83	-0.89	-7.43	-3.80	-3.05	1.72	2.98	0.018	0.037
Dortmund	DE	197.24	7.38	0.56	7.18	2.20	1.74	0.56	1.50	0.032	0.065
Leipzig	DE	-963.88	-19.74	-1.51	-12.79	-10.10	-6.71	0.51	1.39	0.000	0.001
Antwerp	BE	-1536.48	-24.78	-3.08	-15.88	-16.00	-9.78	0.46	0.90	0.010	0.020
Nuremberg	DE	-113.46	-6.33	-0.31	-4.41	-1.50	-1.29	0.33	0.73	0.003	0.006
Bonn	DE	160.81	14.25	0.54	15.49	2.50	2.34	1.14	3.48	0.024	0.049
Verona	IT	335.44	14.64	0.60	14.21	3.80	3.09	0.62	2.75	0.043	0.088
Ghent	BE	-627.48	-7.79	0.09	0.54	-7.20	-3.92	1.85	4.78	0.037	0.075
Lubeck	DE	49.90	0.70	0.19	1.96	0.50	0.28	0.38	1.53	0.013	0.027
Uppsala	SE	-677.07	-24.60	-0.05	-14.65	-9.00	-6.75	0.09	5.52	0.043	0.094
Linz	AT	-792.27	-14.86	-1.37	-9.19	-8.30	-5.35	0.42	0.97	0.004	0.009
Gyor	HU	1268.16	24.74	1.55	28.17	13.50	8.66	1.95	11.69	0.153	0.322
Bruges	BE	915.29	8.52	1.14	8.94	12.40	5.59	1.58	5.99	0.000	0.001
Lund	SE	-217.28	-8.15	-0.02	-1.68	-2.80	-2.13	0.21	4.78	0.006	0.013
Osijek	HR	860.62	59.66	0.64	47.67	12.50	10.73	0.26	2.39	0.118	0.260
Lincoln	UK	-1169.66	-39.20	-3.37	-31.69	-14.30	-10.82	0.09	0.20	0.000	0.001

6.6 Appendix F: Changes is *WSPC* and *WUP* in different population size categories

Table 26 Results of statistical analysis on absolute and relative changes in urban sprawl in different population size categories.

Tests		Outputs Group 1: with greenbelt Group 2: without greenbelt	Changes is *WSPC* in different population size categories (2006 – 2015)					
			WSPC Absolute Changes (UPU per inhabitant or job)			*WSPC* Relative Changes (%)		
			Very Large and Large	Medium-Large	Medium	Very Large and Large	Medium-Large	Medium
Kruskal Wallis test / t-test	For differences in the means	*p*-value	0.0063	0.37	0.11	0.0023	0.14	0.012
		Mean in group 1	-163.19	-186.05	-439.934	-46.35	-12.81	-27.84
		Mean in group 2	-23.20	-257.40	9.68	57.43	21.61	2.54
	For differences in the means of decreased values	*p*-value	0.60	0.33	0.42	0.19	0.83	0.072
		Mean in group 1	-163.19	-208.42	-544.10	-46.35	-26.54	-35.99
		Mean in group 2	-118.01	-533.03	-696.75	-24.17	-14.342	-18.92
Mood's Median test For differences in the medians		*p*-value	0.0037	0.21	0.21	0.0037	0.21	0.0035
		Median in group 1	-117.47	-163.47	-584.43	-50.10	-12.69	-24.24
		Median in group 2	0.44	-1.29	49.90	25.93	-5.44	0.70
Binomial test of Proportions For differences in the proportions of decreased values		*p*-value	0.0098	0.15	0.18	0.0098	0.15	0.18
		Proportion in group 1	1.00	0.91	0.82	1.00	0.91	0.82
		Proportion in group 2	0.25	0.54	0.45	0.25	0.54	0.45

Tests		Outputs Group 1: with greenbelt Group 2: without greenbelt	Changes in *WUP* in different population size categories (2006 – 2015)					
			WUP Absolute Changes (UPU per m^2 of landscape)			*WUP* Relative Changes (%)		
			Very Large and Large	Medium-Large	Medium	Very Large and Large	Medium-Large	Medium
Kruskal Wallis test / t-test	For differences in the means	*p*-value	0.018	0.22	0.011	0.0023	0.094	0.0098
		Mean in group 1	-0.47	-0.39	-1.24	-41.38	-9.038	-22.63
		Mean in group 2	-0.12	-0.43	-0.0046	71.24	22.30	5.44
	For differences in the means of decreased values	*p*-value	1	0.33	0.72	0.19	1	0.11
		Mean in group 1	-0.47	-0.44	-1.52	-41.38	-22.77	-30.18
		Mean in group 2	-0.64	-1.158	-1.20	-20.42	-11.19	-14.30
Mood's Median test For differences in the medians		*p*-value	0.0037	0.21	0.0035	0.0037	0.21	0.0035
		Median in group 1	-0.22	-0.33	-0.82	-44.81	-9.38	-15.69
		Median in group 2	0.0033	0.0095	0.19	26.20	0.057	1.96
Binomial test of Proportions For differences in the proportions of decreased values		*p*-value	0.0098	0.067	0.083	0.0098	0.067	0.083
		Proportion in group 1	1.00	0.91	0.82	1.00	0.91	0.82
		Proportion in group 2	0.25	0.54	0.45	0.25	0.54	0.45

Legend	
Highly Significant	< 0.01
Significant	0.01 – 0.05
Marginally Significant	0.05 – 0.1
Not Significant	> 0.1
NA	NA

6.7 Appendix G: Diagrams of absolute changes in *WSPC* and *WUP* as a function of population size

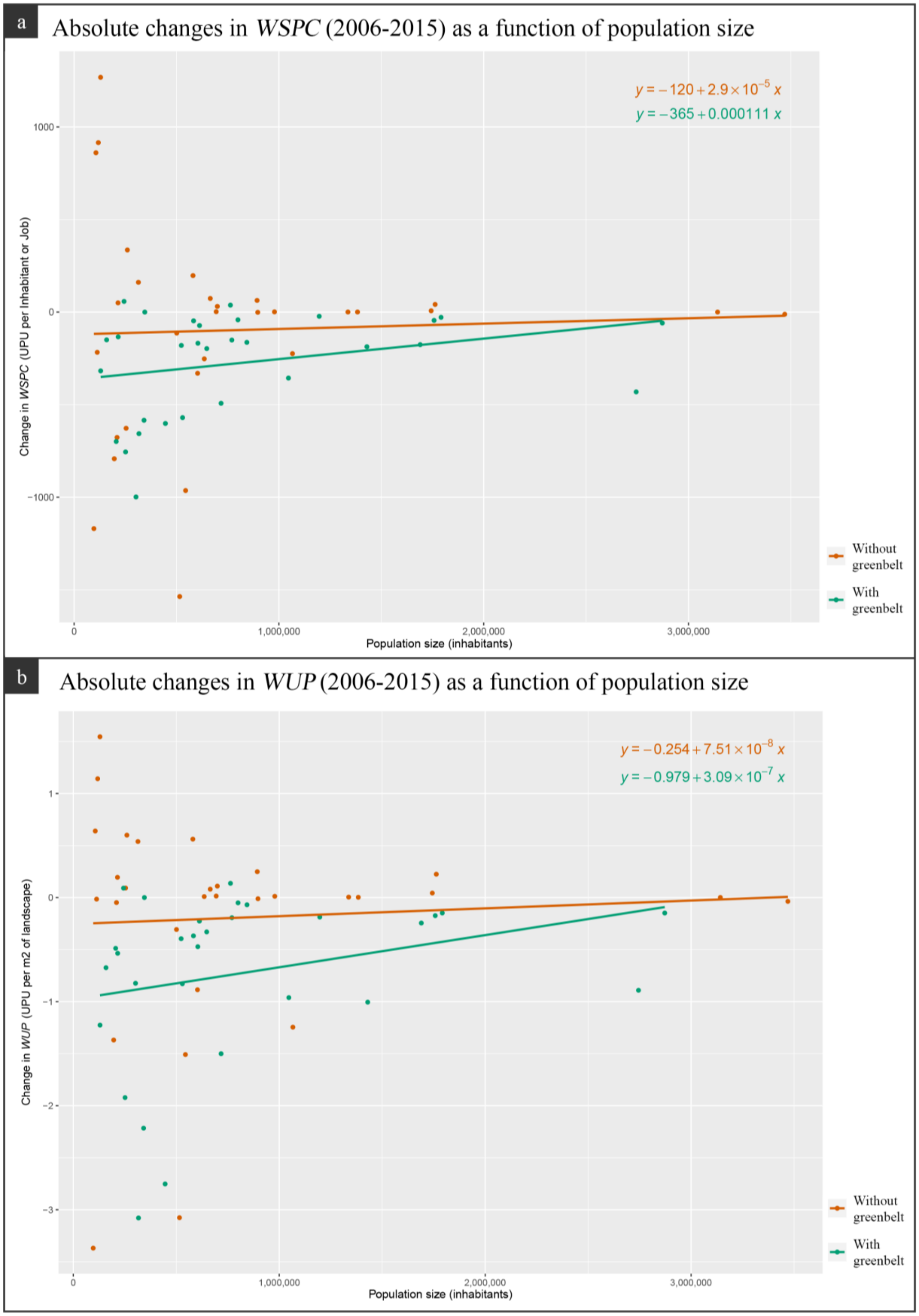

Figure 16 Absolute changes in (a) *WSPC* and (b) *WUP* in the cities without greenbelts (orange) and with greenbelts (green) as a function of population size (Orange: R^2-*WSPC* < 0.01 and R^2-*WUP* < 0.01; Green: R^2-*WSPC* = 0.08 and R^2-*WUP* = 0.07).

6.8 Appendix H: Diagrams of *WSPC* and adjusted *WUP* in 2006

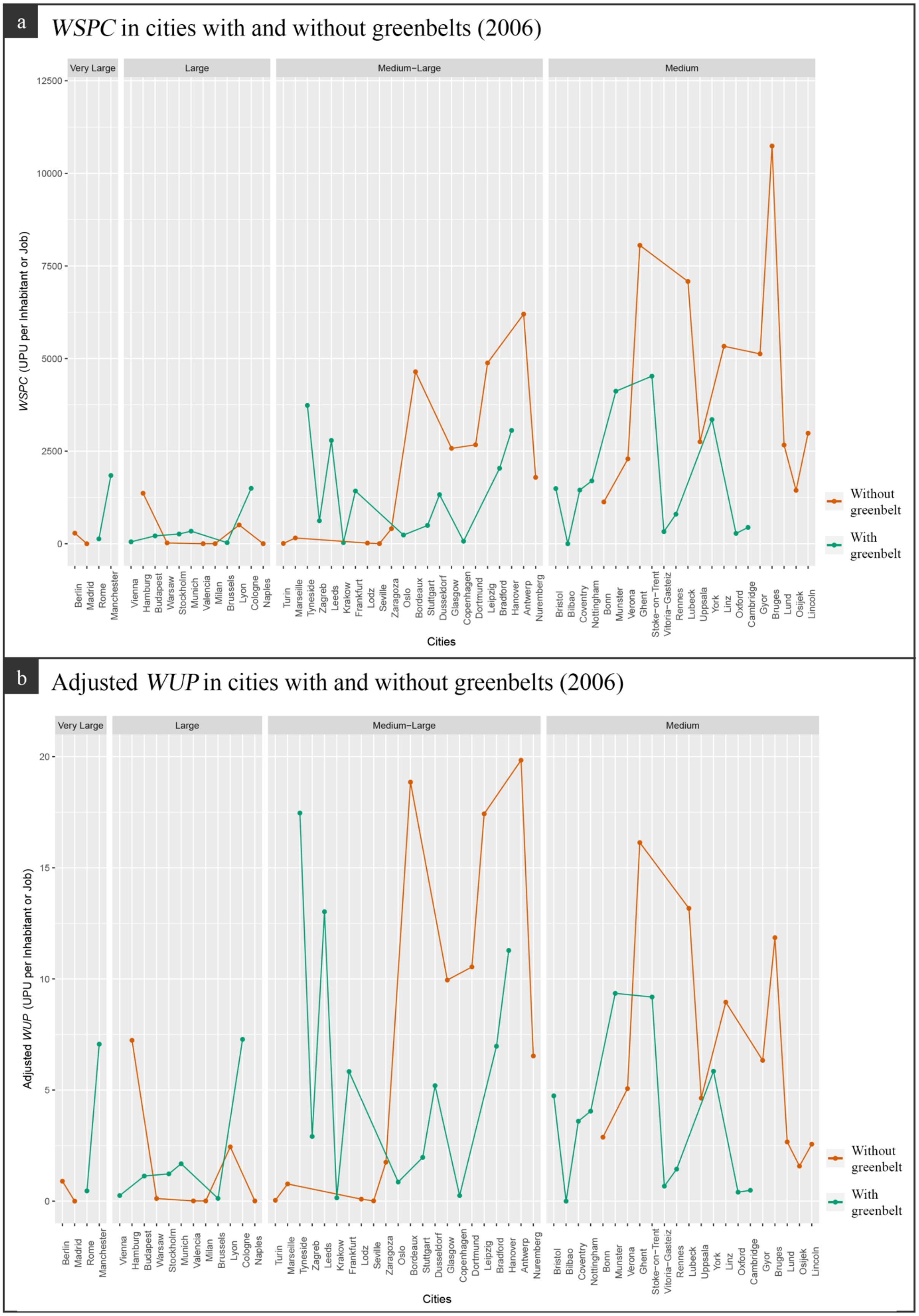

Figure 17 Diagram of (a) *WSPC* and (b) Adjusted *WUP* values in the cities without greenbelts (orange) and with greenbelts (green), in 4 population-size categories (2006).