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The Policy Relevance of Urban Scaling Laws: A Study on Impervious Ground in German Cities

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ABSTRACT

The expansion of urban infrastructure is an important indicator of agglomeration and a major factor in the deterioration of the urban environment. The investment in urban infrastructure is accompanied by the sealing of ground. The implementation of effective policies to reduce the practice of sealing ground is impeded by the existence of conflicting interests and fiscal disincentives. A significant challenge is the dearth of policy-relevant information. Conventional analysis considers urban outcome indicators in proportion to population and neglects non-linear distribution patterns, thus obscuring global regularities that contain important information. The study contributes to a more comprehensive understanding of urban imperviousness through the lens of urban scaling. The present study employs Germany as a case study to examine the extent to which the parameters of the scaling function differ between two types of cities. District Affiliated Cities (DACs) and Administrative City Districts (ACDs), which are afforded greater fiscal autonomy. The analysis indicates that the amount of sealed land exhibited a notable increase between 2006 and 2018 in the ACDs. Calibration of the scaling functions for cities with the actual coefficient of the DAC control estimate and a global orientation exponent (5/6) resulted in a 16% reduction of sealed ground. In conclusion, urban scaling laws offer a valuable tool for analyzing the complex dynamics of urban imperviousness and its control costs, thereby contributing to the formulation of more effective urban policies and planning.

KEYWORDS

Urban Scaling; Imperviousness; Sustainable Development; Urban Economics; Urban Policy

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1. Introduction

This paper addresses the assumption of substantial policy relevance of urban scaling by comparing the volume and dynamics of land sealing in two different administrative types of German cities. Although the study only opens a unique perspective on a narrow focus in a particular country, it can illustrate the patterns of environmental externalities and distorted prices of urban land, and how the closing and widening gaps between the existing and a sustainable state of urban land use can be monitored. To date, the management of environmental externalities in urban contexts has been largely hampered by financial interest and insufficient information about control costs, and by hasty and ill-conceived policy decisions that may encourage uncontrolled urban growth (Correia and Roseland 2022). The growing global burden of negative agglomeration externalities calls for smart urban policy solutions. A key enabler for better policies is information.

Evidence of scaling in different urban contexts reflects the lawful interplay of urban inputs and outputs in relation to city size and can contribute to a more realistic valuation of urban resources such as land. The simple allometric relationship between population size and various urban "outcomes" and the globally characteristic shapes of power functions contain substantial information. The idea for this study was largely inspired by a recent collection of papers entitled "Cities as Complex Systems" (Rybski and González 2022; Arcaute and Ramasco 2022). Urban scaling laws are the focus of most of these papers; their results show that an enormous amount of information can be extracted from these laws. The research field of urban scaling and cities as complex systems has gained increasing attention, but the relevance of scaling laws in the context of urban policy still seems to be largely underexplored.

The fact that, at the macro level, there are several impressively stable relationships between urban size (population) and various urban outcomes, as indicated by characteristic power distributions (Bettencourt et al. 2007), suggests that such scaling laws have the potential to provide guidance for national urban policies and related efforts to adjust spatial planning and investment. Urban policies and planning could thus become smarter.

The overall purpose of this study is to explore the important information gain from urban scaling for sustainable public infrastructure investment in an exemplary way, thus addressing a problem of urban political economy of the environment and its related policy relevance. In the UGEC Viewpoints blog, Michail Fragkias highlighted the importance of complexity science in urban policy. So far, this discussion has largely focused on urban CO_2 scaling (Fragkias 2015). More recently, Kaufmann et al. (2022) investigated the scaling of urban amenities in the context of urban spatial planning. In fact, the information gain of urban scaling is not only generated by the different characteristic scaling parameters, but also reflects central insights of urban economics (e.g. Krugman 1991; Fujita et al. 1999; Henderson 1974; Black and Henderson 1999). In economic terms, sublinear and superlinear urban scaling is largely explained by the existence of increasing returns to scale in urban environments. Due to agglomeration advantages, knowledge and production outputs are growing over-proportionally while the required urban infrastructure (i.e. the built environment) grows under-proportionally with city size.

Imperviousness is one of the urban infrastructure outcomes that follows a scaling law. While there are major culturally determined differences in soil sealing patterns among countries (due to different traditions and building codes), one can observe a ubiquitous characteristic elasticity (with a narrow spread) in the scaling function, despite the fact that there are different rates of urbanization worldwide. In any case, there is an expansion of urban infrastructure and a huge negative impact on biodiversity and greenhouse gas pools (Seto et al. 2012). While the ratio of population to impervious surface varies globally and dynamically, the scaling parameter remains impressively stable. Interestingly, there are institutionally driven perturbations that can affect the distribution of certain desirable (e.g., innovation) or detrimental (e.g., environmental degradation) urban outcomes. Soil sealing can lead to beehive deaths, river flooding (if there is an overabundance of commercial and residential infrastructure in floodplains), and seasonal or permanent urban heat with enormous public health implications, especially for the elderly. In addition, land sealing generates negative urban externalities that are least immediately visible, but cumulative in nature and widespread in distribution (Correia and Roseland 2022). This externality problem therefore deserves special attention.

The specific approach of this paper is to investigate scaling patterns of soil sealing in German cities organized as their own administrative district ("kreisfreie Stadt") compared to those cities that are part of a rural district ("kreisabhängige Stadt"). The simultaneous observation of two types of cities with different administrative powers and a large overlap in population size allows for a direct comparison of elasticities in distribution functions that could potentially be implied by these powers. In the context of this paper, policy relevance requires information on whether there is a significant deviation from a characteristic scaling law that could be corrected by active or passive intervention. In certain cases, such a deviation may result from specific administrative rules and associated incentives or disincentives for public and private agents. This can be relevant for both excessive undesirable urban outcomes and insufficient desirable outcomes.

Apart from a plethora of studies that shed light on various urban phenomena from a scaling perspective, such as urban production, innovation, carbon emissions and traffic accidents (Ribeiro et al. 2021; Strano and Sood 2016; Lobo et al. 2013, Fragkias et al. 2013; Broekel et al. 2023; Cabrera-Arnau et al. 2020), it must be noted that the international literature contains little on the potential policy relevance of scaling laws, neither globally nor specifically for Germany as the selected case study in this research. With regard to urban imperviousness in Germany, there is extensive research on its environmental impacts (e.g., Artmann 2015; Strohbach et al. 2019), but the potential information content of sealed land in the context of urban scaling has not yet been systematically explored.[1]

2. The research hypothesis and its economic context

There are several determinants of urban land sealing. These include a city's importance to the regional labor market, commuting patterns, lifestyle and consumption patterns, and economic activity (Behnisch et al. 2016). Most importantly, urban land sealing is directly determined by urban infrastructure investments.

In theory, infrastructure investments such as land sealing follow a utility function. The availability of roads, paths, and plazas enables efficiency gains in transportation; paved surfaces are necessary for industrial production and social life. At the same time, land sealing consumes valuable and depletable ecosystem services. The marginal benefit is decreasing, while the marginal cost of environmental damage is increasing. According to the standard economic efficiency model of pollution, the maximum benefit is found at the intersection of the two curves (equilibrium) and there are no non-convexities. By estimating both functions, it is possible to quantify the equilibrium (Butler and Maher 1982; Turner 2000, p. 590). Such modeled systems would have constant returns, and urban scaling (see below) would be linear.

Real-world urban systems, however, generate particular advantages for productivity and innovation that are determined by low intra-urban transportation costs, knowledge spillovers, and numerous amenities within reach. In this way, the urban environment favors the development and production of tradable products and services and depends on a growing active population. The relationship between the development of such urban agglomeration economies and population has been empirically estimated by several authors. Melo et al. (2009), who included 729 elasticity estimates in a large meta-study, report an average increase in per capita productivity of 5.8 percent when the urban population doubles. This empirical result suggests a superlinear scaling of urban aggregate output and/or a sublinear scaling of inputs.

[1] With a focus on land use modeling, Tuia et al. (2017) used - inter alia - scaling of land cover to train a model to classify local climate zones in the German Bundesland Northrhine-Westfalia.

The associated agglomeration effects by specialization (Marshall-Arrow-Romer) and diversification (Jacobs) are explained by the characteristic increasing returns to scale in the urban economy as expressed by Henderson (1974):

$$Y_g^{1-\rho} = K^{\gamma} L^{\zeta} \quad (1)$$

Where Y_g means aggregate output of tradables and K and L are the production factors capital (land included) and labor while the sum of the parameters γ and ζ equals unity. The degree of increasing returns is indicated by ρ, where $0<\rho<1$, so that in contrast to the Cobb-Douglas type production function with constant returns (ρ=0) we get:

$$\frac{\gamma + \zeta}{1 - \rho} > 1 \quad (2)$$

Urban aggregate output and urban infrastructure are functionally related as an input-output system, and together they imply increasing returns to scale, so that output increases over-proportionally while infrastructure costs decrease over-proportionally, as indicated by 1-ρ.

Increasing returns to scale imply non-convexities that are not present in the standard model. More importantly, urban agglomeration economies are not time-invariant systems. At some point, competitive markets begin to lose efficiency due to the increasing market power of fewer agents, which jeopardizes the continued sustainable and decentralized allocation of resources, including depletable ecosystem services such as land for development. Market power then overrides price signals for scarce resources, resulting in welfare losses such as congestion or pollution. This can be illustrated by the empirical relationship between city size and utility, which takes an inverted U-shape (Fujita et al. 1999, p.19). One reason for this is that the interests of the private and public sectors coincide in the sense that high profits imply the expectation of high tax revenues, which - at the expense of depletable resources - should increase the public sector's room for maneuver accordingly. This particular pattern can be demonstrated by empirically examining the scaling of land imperviousness in the two administrative types of German cities.

The financial power of public and private urban agents is closely related to the different scope for investment in urban infrastructure. Due to a substantially higher level of gross value added per capita, German cities with their own administrative district (Administrative City Districts - ACD) are assumed to have greater financial power for public investment compared to a rural district. For the period 2014-2016, Hesse et al. (2019, p. 705) report tax revenues per capita in ACDs of around 1,200 euros on average, compared to only 870 euros for rural districts. Thus, ACDs have about 35-40 percent higher tax revenues than rural districts. Even though cities and larger municipalities within these districts (District Affiliated Cities - DACs) may have higher per capita tax revenues than the smaller villages around them, it is likely that there is still a substantial revenue gap compared to ACDs. This may have some relevance for the urban environment and the climate problem, as there is an obvious assumption that cities with more financial power can also invest larger amounts of public funds in urban infrastructure, ultimately leading to more impervious surface. This phenomenon is not only a typical German problem, but can also be observed in other countries, probably worldwide (e.g. Ye and Wu 2014; Ewing and Hamidi 2015). But urban land sealing is not only affected by the one-way logic described above; land consumption itself is an important incentive to generate more gross value added and, ultimately, local tax revenues. This peculiar coincidence of public and private interests is well described by Langer and Korzhenevych (2018). In their empirical study of Bavaria, they show that an increase in municipal built-up and industrial areas has a significantly positive effect on local tax revenues. Using OLS and further refined instrumental variable (IV) models (with and without control variables), they show that each additional hectare of developed land generates on average 13,000 euros in tax revenue, empirically proving the hypothesis described above. The effect is greater in more densely populated municipalities. From an environmental point of view, this vicious circle of "tax revenues - investment in soil sealing - additional tax revenues" is a fundamental factor in the degradation of nature in urban regions with growing congestion effects. The problem as such is closely related to the determinants of land value, rent and land use, which have long been addressed in seminal contributions to regional science (e.g. Lösch 1954, Isard 1956, Lefeber 1957, Alonso 1964). Only later was the problem of environmental externalities of urban land development recognized and taken into account more explicitly (e.g. Richardson 1977).

3. Methodology

The two administrative types of German cities allow a direct examination of a possible administrative bias in the distribution of urban imperviousness. In terms of urban population size, there is a larger overlap between the two types of cities in the range of 35,000 and 3.6 million inhabitants (Figure 1).

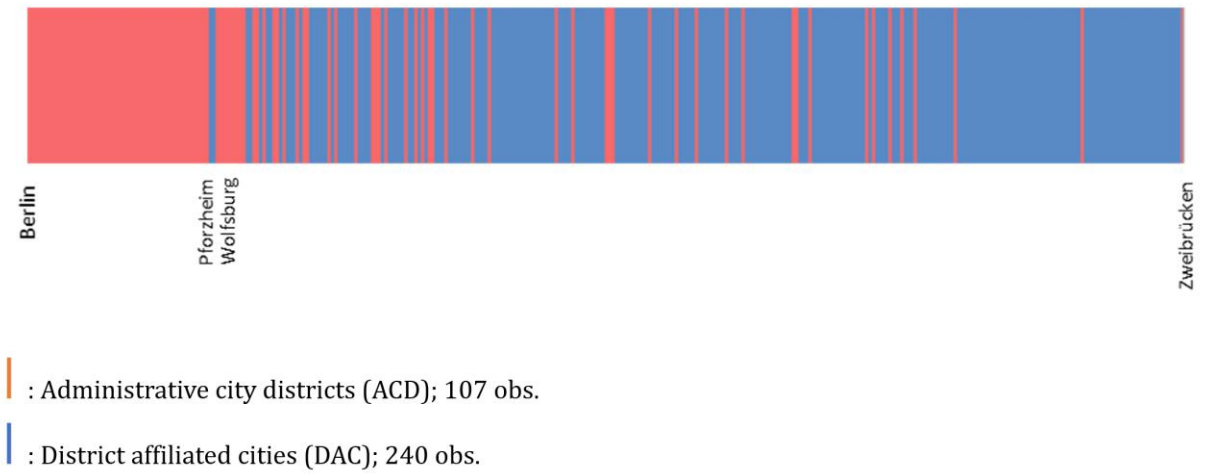


Figure 1. Overlap of city type distribution (ranked).

Data source: Destatis (data file: Cities in Germany by area, population and population density 31 December 2021).

Thus, by examining ACDs, it is possible to directly identify a control sample of DACs (determined by size) and estimate the different levels and trends of urban soil sealing along the selection shown in Figure 1. A remaining problem is the unavailability of a DAC control distribution for the homogeneous red upper tail (Berlin to Pforzheim), which means that we cannot create a sample of DACs along the same size range as for the ACDs. To solve this problem, only smaller ACDs (Wolfsburg to Zweibrücken) are replaced by district affiliated cities of the same size. Thus, a homogeneous ACD and a hybrid ACD-DAC distribution are compared using the scaling law of urban imperviousness. It is important to note that ideally the total population of both samples must be identical.

One question raised in the initial discussions of this paper was why urban scaling was used for this research in the first place. A relatively simple approach to comparing land sealing in ACDs and DACs could be to examine per capita imperviousness in both types of cities and perform a simple t-test to detect significance in the difference in means. However, the information gained from such a method would be limited because it ignores the known global non-linear relationships along the size range of cities. Thus, a simple comparison of means would result in imprecise findings and a lack of empirical guidance. More importantly, the size range of ACDs is much broader than that of DACs; in particular, the distribution of paved land in larger cities would remain unconsidered by simply comparing the per capita imperviousness of the two types of cities. In contrast, the scaling law analysis (Bettencourt 2013) allows both (i) the detection of the ratio between population and sealed land and (ii) the estimation of the shapes of the power distribution of sealed land (and thus the deviation from a global benchmark) for the two respective city distributions considered. In this way, it is possible to identify critical sections along the distribution of cities and to simulate the total impervious area with adjusted parameters, so that for each city the differences between real, estimated and benchmark imperviousness can be calculated.

Methodologically, I distinguish between a sample of exclusive ACDs and another in which the lower tail is replaced by DACs of comparable size. The study period is 2006, 2009, 2012, 2015 and 2018. The information base of the study consists of land imperviousness data provided by the IÖR-Monitor (www.ioer-monitor.de) in addition to official population and spatial city size data published by Destatis.

As mentioned above, urban scaling can be applied to show the sub-linear, linear or super-linear changing proportion of any urban outcome in relation to population size (e.g. production, sealed land, pollution, political power or rank in the urban system, like the famous Zipf's law), either for time series or cross-sectional analyses.

Urban scaling is defined as a simple allometric relationship:

$$Y \sim S^{\beta} \tag{3}$$

showing that any output Y (a variable such as infrastructure or aggregate output) corresponds to the population size S of a city, with the exponent β indicating whether there is a convex or concave relationship for a city over time or within the distribution of all cities at a given point in time. Several authors emphasize the direct relationship between urban scaling and the development of an urban agglomeration economy (Lobo et al. 2013; Gabaix 2016; Sarkar et al. 2020). Increasing returns in this setting are reflected in a superlinear scaling of economic benefits (i.e., production and innovation) and a sublinear scaling of input costs (e.g., urban imperviousness Y_m).[2] Moreover, this interplay of costs and benefits in urban systems is impressively stable globally, and has been described by Webster (2024) as another curiosity in addition to Zipf's law for cities. Theoretically, the effects of urban agglomeration can be estimated up to the global level on the basis of the respective scaling function.

The total impervious area Y_M of a sample of n differently large cities with size S_1 to S_n is thus:

$$Y_M = \sum_{i=1}^{n} \alpha S_i^{\beta} \tag{4}$$

with α and β pre-estimated. Globally, the β-exponent has been shown to be about 5/6 (0.83) for urban infrastructure (Zünd and Bettencourt 2019; Liu et al. 2022; He et al. 2023; Xu et al. 2023). Brelsford et al. (2020) also confirm this theoretical benchmark for urban imperviousness in the USA. Ma et al. (2018) explore the issue of land imperviousness by scaling it with the extent of urban area in three Chinese metropolitan regions. Compared to estimates with population (as the usual predictor), they find a superlinear scaling (>1.1). This is explained by a greater increase in soil sealing than the respective urban area. When urban area is replaced by population, the results confirm the typical sub-linear scaling.

It should be noted that several authors have questioned the validity of different urban scaling laws. Arcaute et al. (2015) reject several urban scaling laws in their research on England and Wales, but admit that a large distorting effect may be due to the weight of London as a global megacity in a relatively small country. Barthelemy (2019) finds stable linearly scaling urban indicators, but fluctuating exponents when nonlinear scaling is present. Cottineau et al. point to the Modifiable Areal Unit Problem (MAUP) and heterogeneous morphologies within cities and a resulting large variation in scaling. Varying estimates depend largely on the definition of city boundaries, whether

2 The derivative of equation (3) reflects scale economies and illustrates how production output grows superlinearly in relation to population size or how the marginal cost of providing urban infrastructure decreases as population size increases: $Y' = \alpha\beta P^{\beta-1}$. Related to the above mentioned production function (1), and assuming a constant labor participation rate in the population, it can be deduced: $\frac{\partial Y_g}{\partial L} > 1 \, and \, \frac{\partial Y_g}{\partial K} > 1$.

statically administrative or dynamically natural. The MAUP is also present in Zipf's law for cities, the most studied urban scaling law (e.g., Bergs 2018; Budde and Neumann 2019). These limiting factors are important to consider for any analysis of urban scaling, and one should definitely relax overly strict definitions of scaling landmarks, such as taking exactly 0.83 for impervious area. However, for time series or panel analyses, such indicative landmarks seem to be quite useful to detect widening and closing gaps between expected and estimated distributions and to simulate realistic "what if" scenarios. A simple exercise is included in this paper.

The empirical analysis in our study includes regression analyses for (i) the entire distribution of ACDs and (ii) a hybrid distribution of upper-tail ACDs merged with lower-tail DACs to explore a possible different pattern of soil sealing in both samples. In these regressions, the simple comparison of these five years could ignore a possible temporal influence of earlier on later years. Therefore (iii), as suggested by Brelsford et al. (2020), we additionally use a between-estimator:

$$\overline{y}_{m,i} = \alpha + \overline{s}_i\beta + u_i + \overline{\varepsilon}_i \tag{5}$$

where u_i is the time-invariant individual effect.

For the panel analysis, it should be noted that the ranks of city size changed for only a few cities during the period under consideration, partly due to territorial reforms. Therefore, there may be some small errors in the estimates. The base year is 2006.

4. Results

Data published by the IÖR suggest a rather constant impervious area per capita in Germany between 2006 and 2015, and then a rather peculiar increase of almost 19 percent between 2015 and 2018, as shown by the bold line in Figure 2. On average, however, per capita imperviousness is lower in larger cities. The lowest values are found in cities such as Berlin, Munich, Stuttgart, Essen or Düsseldorf (between 80 and 112 square meters in 2018). Moreover, the values remain constant over the observation periods. Many smaller ACDs, such as Emden, Zweibrücken, Dessau, Wilhelmshaven and Brandenburg, have very different levels and trends of land sealing, as shown in Figure 2.

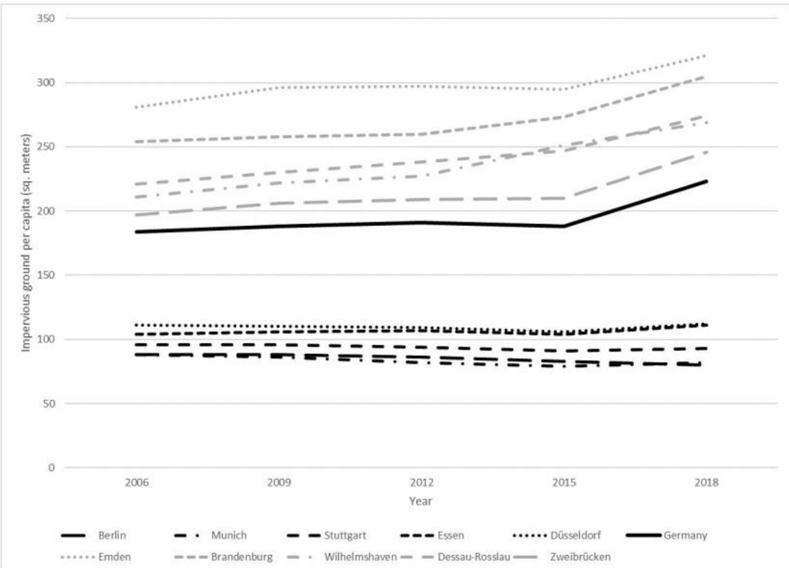


Figure 2. Impervious ground per capita 2006-2018: Selection of larger and smaller ACDs compared to the overall trend (Germany).

Data Source: IÖR.

This trend can also be seen in Figure 3, which compares the small ACDs and the control sample from the DACs. The trends are similar, but the amount of impervious land is greater and growing slightly faster in the smaller ACDs. The populations of the DAC cities and the respective lower tail of the ACD cities are almost identical, even slightly larger in the DAC sample.

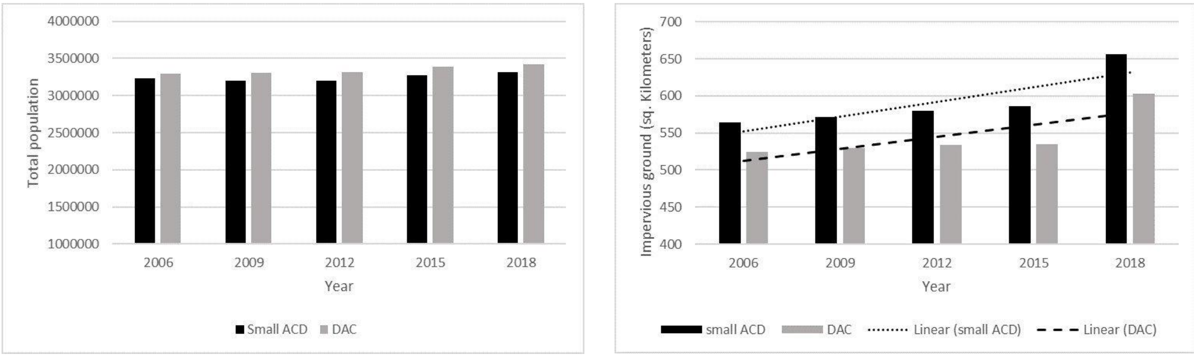
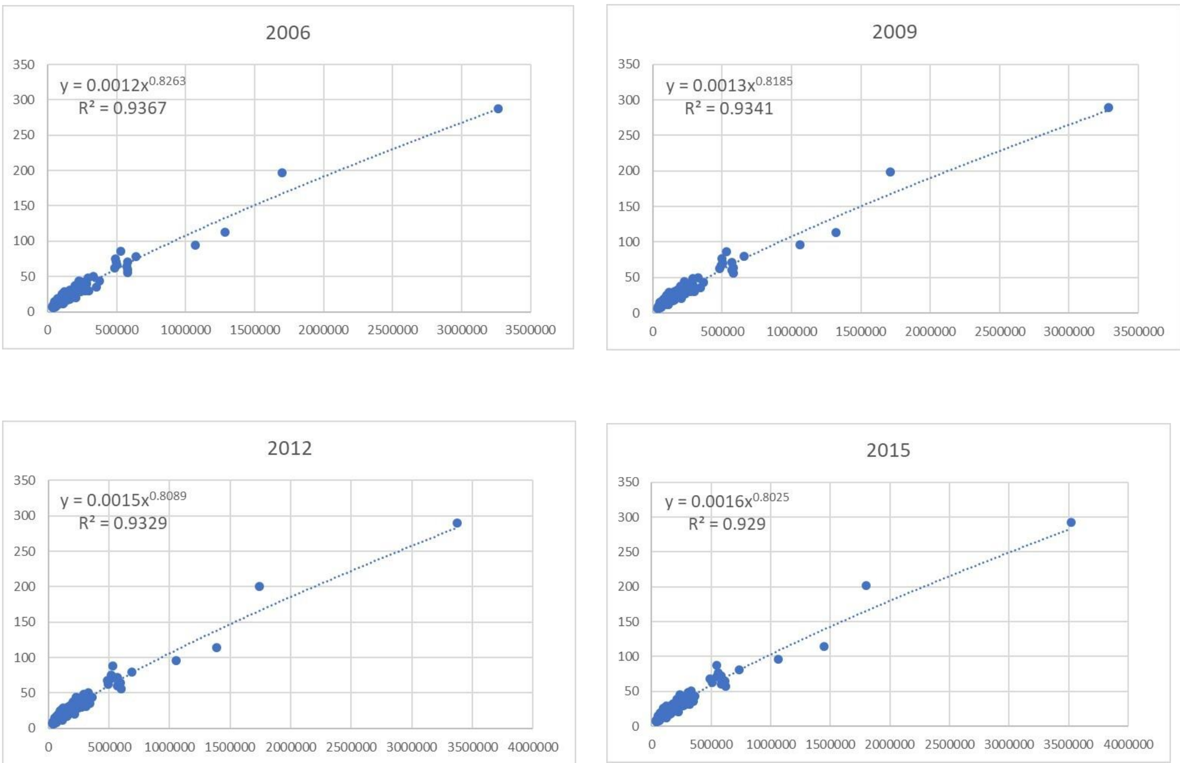


Figure 3. Population and impervious ground of the smaller ACDs and the control sample of DACs.

Data source: IÖR and Destatis (n=47 for small ACDs and DACs respectively)

How do these descriptive statistics on land sealing and population translate into an urban scaling law? The empirical results of the scaling estimates are structured into the simple power regressions per year considered (Figures 4 and 5) and the panel regressions to compare the elasticity of land imperviousness in the homogeneous ACDs and the combined ACD-DAC sample (Table 1).



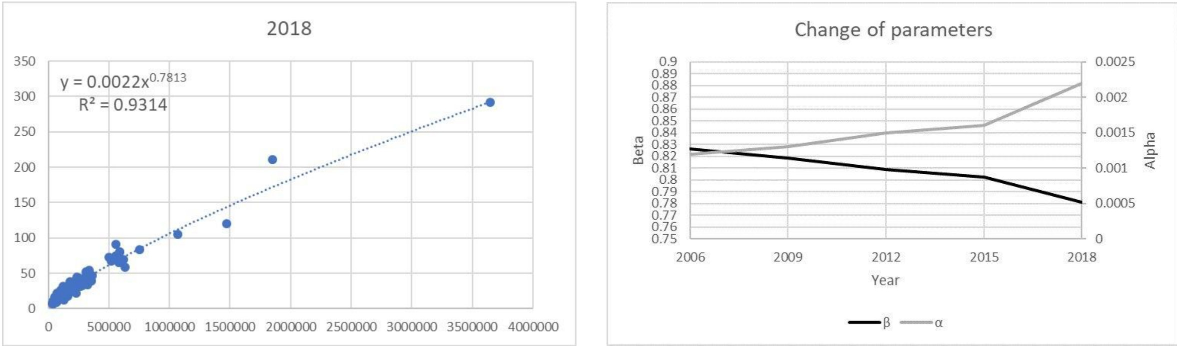


Figure 4. Scaling of impervious ground: All administrative city districts (ACDs).

Notes: Unless otherwise stated: X-axis: city population S; Y-axis: sealed soil Y_m (square kilometers); for all estimates: $p \leq 0.01$. Data source: IÖR and Destatis (n=107).

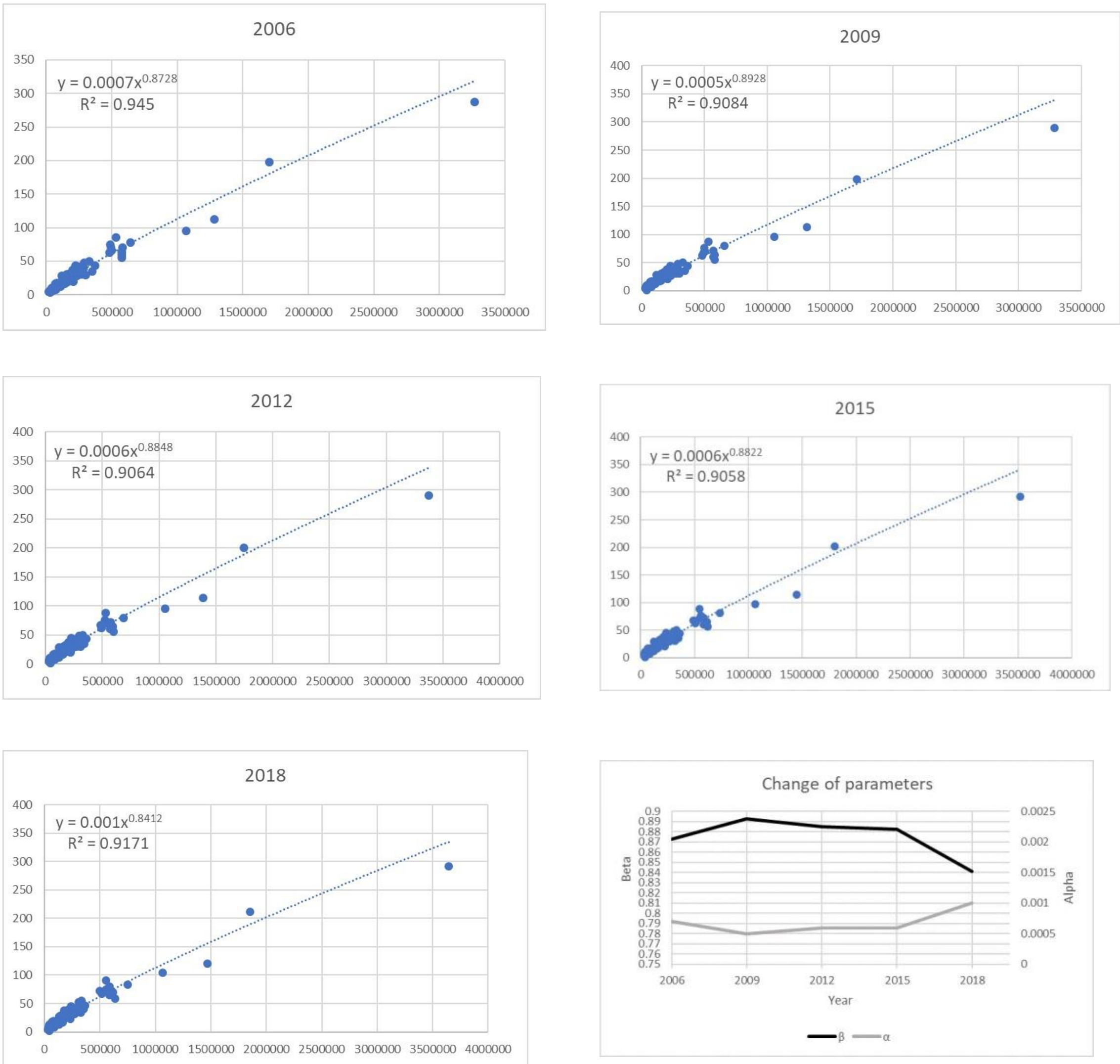


Figure 5. Scaling of impervious ground: Lower tail of ACDs replaced by district affiliated cities (DACs) of same size.

Notes: Unless otherwise stated: X-axis: city population S; Y-axis: sealed soil Y_m (square kilometers); for all estimates: $p \le 0.01$. Data source: IÖR and Destatis (n=107; n_{DAC}=47).

Table 1. Scaling of impervious ground: Regression results for all administrative city districts (ACD) and for the sample with the replaced lower tail (ACD-DAC).

VARIABLES	(1) log (Y_m)	(2) log (Y_m)	(3) log (Y_m)	(4) log (Y_m)
log (S)	0.808***	0.808***	0.875***	0.876***
	(0.0095)	(0.0156)	(0.0116)	(0.0190)
Constant	-6.493***	-6.497***	-7.350***	-7.358***
	(0.113)	(0.185)	(0.138)	(0.227)
Observations	535	535	535	535
R-squared	0.932	0.932	0.915	0.915
Number of id		107		107

Note: (1) Linear regression ACD; (2) Panel regression with between estimator (ACD); (3) Linear regression (ACD-DAC); (4) Panel regression with between estimator (ACD-DAC); Data source: IÖR and Destatis. Standard errors in parentheses.
**** p<0.01, ** p<0.05, * p<0.1.*

Whether comparing different years and city samples, or comparing different city samples in a panel approach, we find a significant difference between the pure ACD sample and the DAC-replaced sample for the lower tail. The nonlinear (power) comparison of the two samples shows a more concave pattern for the pure ACD sample, while the lower-tail replaced sample is closer to linearity. This shows a relatively higher per capita imperviousness in the smaller ACDs compared to the replaced cities sample. The larger the ACDs, the lower their per capita imperviousness appears to be, consistent with the typical sub-linear urban power law of infrastructure. Furthermore, land imperviousness has increased over time in both samples. However, in the ACD, the pattern shows an increase in α and a decrease in β, while there are no such trends in the ACD-DAC sample. This reflects the relative increase in impervious cover in smaller ACDs compared to larger ones. The trends of the constant α and the exponent β (parameter changes) appear to be essentially mirror images for the two samples considered. This is due to the increase of sealed soil in the smaller ACDs (see Figure 2). The lower tail of the power curve was shifted slightly upwards, while the upper tail remained fixed. Looking at the panel analysis, we see negligible differences between the simple linear regression and the between estimates. This is also in line with the results of Brelsford et al. (2020), who examined US Metropolitan Statistical Areas based on census data. The elasticities estimated in this study are close to 5/6 and thus similar to our results. However, we found a stronger elasticity - i.e., estimates for log(S) - for the sample with ACDs replaced by DACs in the lower tail (i.e., a one percent increase in population leads to 0.88 percent increase in land imperviousness, while it is only 0.80 percent for the sample with only ACDs). This shows both a significantly lower level and a weaker trend of land sealing over time for DACs compared to the smaller ACDs. This finding is consistent with the descriptive statistics shown in Figure 2 and Figure 3. What is surprising at first glance, namely a higher elasticity for the hybrid ACD-DAC sample, is explained by the more stretched distribution of sealed soil. The upper tail (ACDs) raises the exponent β by ten percent to 0.88. In addition, the base of the curve is much lower. This draws attention to the coefficient α. Typically, research on urban scaling laws focuses on the characteristically stable exponent β at the macroscopic level, and largely ignores patterns in the constant α. However, the constant is still important when it comes to studying total urban outputs, such as the amount of impervious urban space in a given country.

The direct relevance of this can be demonstrated by comparing the actual ground imperviousness of the ACDs in 2018 with a function calibrated with the α coefficient from the 2018 ACD-DAC regression and 0.83 as a global reference value for the exponent β. Thus, α can be interpreted as a recent national benchmark from the hybrid ACD-DAC sample (the difference between the constants in both samples is thus considered as excess impervious ground in the ACDs), while β represents the global orientation. This is illustrated in Table 2.

Table 2. Sealed ground in ACDs 2018 and optimized scenarios compared.

<table>
<tr><th></th><th>Total sealed ground (real):
$Y_m = 0.0022 \cdot S^{0.7813}$</th><th>Benchmark:
$Y_m = 0.001 \cdot S^{0.83}$</th><th>Adjustment need for β *:
$Y_m = 0.0022 \cdot S^{0.7684}$</th></tr>
<tr><td>Total sealed ground 2018 (square kilometers)</td><td>3,548</td><td colspan="2">2,980</td></tr>
</table>

*Data source: IÖR, Destatis and characteristic parameters (n=107). * If α is kept constant, the scaling parameter must be reduced to 0.7684, i.e. less than 7/9, to match the benchmark total.*

The result would be about 16 percent less imperviousness in the ACD sample. Alternatively, to compensate for the larger α, the exponent β would need to be reduced from 0.83 to 0.7684 to maintain the benchmark for total impervious area. The curve then becomes more curved, as larger ACDs would be required to unseal areas and compensate for increasing land sealing in smaller cities. This is best illustrated by dividing the ACDs into terciles (cutoffs are 95,001 and 212,305 population) and then comparing the position of the gray curve relative to the black curve in the first and third tercile (Figure 6). Note also the strong sensitivity associated with β. A one percent increase in the benchmark exponent (0.8383), while keeping α constant at 0.001, would increase the total impervious area in ACDs by 11.25 percent. This underscores the importance for policy to consider the nonlinear behavior of impervious land in urban systems.

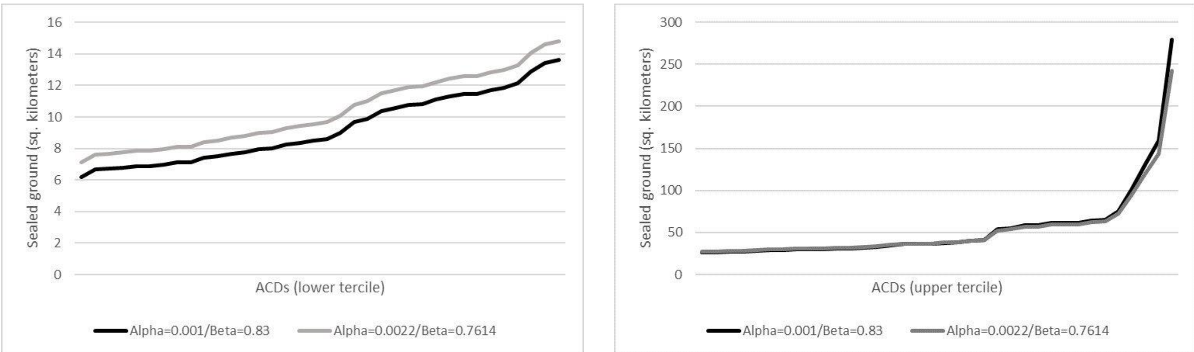


Figure 6. Comparison of varying α versus varying β in distributions with identical totals (2018): First tercile ACDs (left) and third tercile ACDs (right).

Left figure: Lower tercile of ACDs (Zweibrücken – Gera); right figure: upper tercile of ACDs (Erfurt – Berlin); middle tercile is not reported. Data source IÖR, Destatis; own calculations (n=107).

The relevance for policy and planning can be illustrated by Figure 7. The X-axis represents the unity benchmarks for all ACDs. Positive and negative deviations are displayed by the vertical distance of every observation from the abscissa. Almost all of the 36 smaller ACDs (light gray bar) show excess imperviousness. In the second (dark gray bar) and third tercile (black bar) we find around twenty cities with sealed land below the benchmark. However, also in those sections the majority of cities is affected by excess imperviousness, even though there are some larger cities (e.g. Stuttgart and Munich) that appear substantially "greener“ than expected.

It is neither feasible nor reasonable to set the attainment of each individual city benchmark as a national urban policy goal; the economies of some industrial and port cities simply depend on sealed land, and there may be little scope to unseal large impervious areas in such cities. However, it may be easier for cities with a large share of service industries and administration to adjust the proportions of sealed and green areas. To keep the scenario more flexible, one could still allow a narrow interval of e.g. ±0.01 for the scaling exponent, i.e. $\beta \in [0.82, 0.84]$. The strategic goal is to reduce the slope of the regression line in Figure 7 by focusing on the observations above the abscissa.

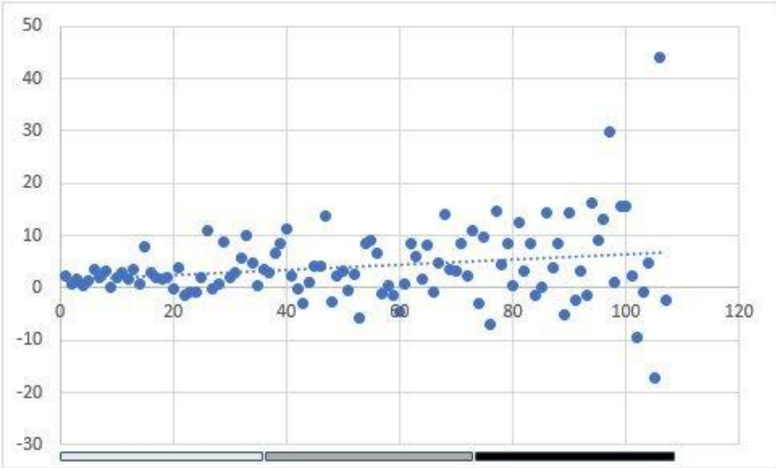


Figure 7. Deviation of urban sealed soil (square kilometres) from benchmark estimates of ACDs in 2018 (benchmark=0).

Bars: First tercile: Zweibrücken – Gera; middle tercile: Schwerin – Oberhausen; third tercile: Erfurt – Berlin. Data source: IÖR, Destatis and application of benchmark parameters (n=107).

5. Discussion

The distribution of urban imperviousness follows a sublinear scaling law, as several international studies, including this one, have shown. The context of this scaling law is an economy with increasing returns, implying market imperfections. While cities are considered the powerhouses of national growth and innovation, such local economies are not in a steady state. The market power of a few urban actors can obscure the true prices of natural resources needed to boost agglomeration economies. This increases the risk of negative agglomeration effects. By linking the phenomenon of increasing returns to an urban scaling law, it is possible to explain the problem of excessive land sealing from an economic perspective and opens up the possibility of evidence-based policies to correct the prices of scarce resources.

The inherent quasi-natural law property (with virtually invariant scaling exponents) makes it a candidate for a specific information tool to guide urban policy and planning to limit unsustainable expansion of urban infrastructure. The difference between real and empirically estimated benchmark imperviousness can be substantial. This is shown by the study of the two different administrative types of German cities. The difference between real and control estimates is substantial and indicates the over-consumption of important urban ecosystem services. However, the results presented above need to be interpreted in a differentiated manner.

An important prerequisite for policy is to take into account the dynamics of urban agglomeration and to recognize a changing balance of benefits and costs. Thus, it is not sufficient to quantify the equilibrium of benefits and damages (costs); the individual level of imperviousness in cities must be related to a changing equilibrium and to the implications of increasing returns, both of which would be quite challenging (Butler and Maher 1982). It is also not sufficient to simply calibrate the scaling function with certain control estimates for α and β to define a national maximum amount of urban land imperviousness. Rather, each city's estimates and their dynamic deviations from the actual amount of imperviousness contain the central information. The advantage of using scaling benchmarks for policy is realized in monitoring the closing or widening of gaps and in considering the different social returns to imperviousness in different cities.

The empirical results for the ACDs - compared to their DAC controls - do not simply suggest that the focus of

German urban policy intervention is on excess and increasing imperviousness in the smaller ACDs, simply because they all have more sealed land than the respective benchmark estimate. Theoretically, smaller ACDs could still grow with a net agglomeration benefit, even though their imperviousness exceeds the benchmark. It would then be uneconomical to slow these cities down with public investment efforts as long as the social benefits exceed the control costs. In absolute terms, imperviousness is clearly greater in the middle and upper thirds of cities. However, larger ACDs may also need to be addressed differently because (i) land sealing in these cities has remained relatively stable and (ii) some larger ACDs are home to important land-consuming industries or critical infrastructure such as ports or airports. Thus, the environmental costs of such sealed land (damage costs) are partially offset by its strategic infrastructure benefits.

The simplest conceivable tool to address urban imperviousness would be an administrative reform of the German urban system, reducing and harmonizing the fiscal powers of cities. This is not politically feasible and certainly not very effective. The internalization of external costs through intelligent regulation has recently been proposed by Correia and Roseland (2022) because market-based instruments have allegedly failed due to market power imbalances and lack of transparency. Here, the authors point to the limitations of the practical application of the Coase theorem and its strong assumption of perfect information and the absence of the assignment problem. Their study does not discuss other market-based solutions that rely on better information and data.

Rather, a potentially feasible tool would be to correct urban land prices and break the vicious cycle of land sealing and increased local tax revenues described above by setting a national limit on the total urban imperviousness budget (similar to a carbon emissions budget) and accordingly penalizing cities with excessive levels of land sealing while rewarding those with low levels of sealing, e.g. the larger "green" ACDs in Germany. Better information can be provided by the scaling-law-determined benchmark of total sealed land and the corresponding deviations for each city. Penalties or rewards for cities are then determined accordingly and are transparent to all market participants.

The expenditure from local tax revenues is thus divided into public investment and penalty. The penalty reflects the real control cost and is independent of any type of administrative city (such as ACD or DAC). Whether local tax rates are kept constant or increased (Pigou tax), there will be a price increase either due to a reduced (or zero) supply of land or due to an increase in the local tax burden. The superiority of each policy instrument to correct prices depends on the respective ratio between marginal benefits and costs, as pointed out by Weitzman in his seminal contribution on the choice between price and quantity (Weitzman 1974).

As the deviation of real imperviousness from the estimate increases, charges (or rewards) to cities - and the share of regular public spending and penalties - will change the budget constraint accordingly. It is then a matter of choice whether to allocate the remaining tax revenue to further land development or to other needs of the municipality. The necessary information is contained in the urban scaling of impervious land as shown in this research. A monitoring system programmed with real and benchmark scaling functions can provide information on critical trajectories of urban imperviousness and thus improve timely information on the costs of controlling land sealing. Such a decision support system could help reduce the distorting incentive for further land development and displacement of urban green space, especially in the smaller ACDs.

The results discussed in this study are specific to the German urban system. A relevant avenue of broader empirical research would be to investigate the relationship between local fiscal autonomy and urban land imperviousness in national urban systems with different rules of local public finance. Another relevant avenue of research could be an extended empirical model to capture the sensitivity to MAUP and possible spatial dependence effects in urban scaling laws (e.g., Bergs 2021; Xiao and Gong 2022). Especially in larger and more culturally diverse countries, patterns of urban infrastructure may differ regionally, so that, at least in theory, there could be a spatial effect on land imperviousness via the distance between cities.

6. Conclusion

The above analysis addresses a narrow focus of urban externalities in a single country. Therefore, it is not possible to generalize the empirical strategy and results globally. However, the results confirm the hypothesis that urban scaling laws contain important information about environmental externalities in urban agglomeration economies. There is an important relationship between scaling and increasing returns in urban contexts.

For the German case, the initial hypothesis of this study is confirmed: The evidence suggests that German cities with their own district administration tend to seal more land than their district-affiliated counterparts. In ACDs, there was a dynamic increase in imperviousness during the period 2006-2018, despite a stable or even temporarily decreasing urban population. DACs do not show such a dynamic trend. However, there must be a reason for such significant differences in land sealing levels and trends between different administrative types of cities of similar size located in an economically integrated area like Germany, even if these differences are small. There are no obvious natural reasons why officials in DACs seal less of their land than their counterparts in ACDs. The granting of ACD or DAC status is simply a political decision. If such a political decision has an impact on the level of local tax revenues, it will automatically affect the spending of local budgets. Since local governments have a strong incentive to attract and retain investment, the size of the local budget is directly relevant to the development of urban infrastructure. Zoning and land development to attract investment and labor, and thus to generate further local tax revenues, essentially leads to land sealing in the city center and, more likely, along the urban fringe. Then, as Harvey and Clark argued some six decades ago, "sprawl occurs because it is economical in terms of the alternatives available to the occupants. (Harvey and Clark 1965). This simple reasoning by local authorities ignores the external environmental costs of land sealing and thus hinders sustainable urban development. The cost-output relationship between a sub-linear urban infrastructure and a super-linear scaling of production reflects the trajectory of an urban agglomeration economy, further reinforced by concentrated market power and price distortions. A - so far - "clumsy" management of the "wicked" problem of urban land sealing (Artmann 2015) could possibly be improved by better information, taking into account the respective urban scaling law. By monitoring both the scaling exponent (as a global benchmark) and the constant, the analysis of urban scaling provides meaningful policy information on (i) an indicative maximum national budget for sealed urban soils, (ii) the ongoing closing or widening of gaps between tolerable and actual imperviousness, and (iii) the identification of cities with conspicuous soil sealing patterns compared to other cities over time. Thus, reliable monitoring of imperviousness scaling will contribute to smarter urban policy and planning. How best to individually address excessive or increasing imperviousness in cities, whether through regulation or market instruments, remains to be further explored for the different urban systems.

Taken together, the above results seem to be relevant for the urban political economy and the expenditure part of local public finance.

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Conflict of interest

The author claims that the manuscript is completely original. The author also declares no conflict of interest.

References

Alonso W (1964) Location and land use: Toward a general theory of land rent. Cambridge (Mass.): Harvard University Press

Arcaute E, Hatna E, Ferguson P, Youn H, Johansson A, Batty, M (2015) Constructing cities, deconstructing scaling laws. *Interface* 12: 20140745. https://doi.org/10.1098/rsif.2014.0745

Arcaute E, Ramasco JJ (2022) Recent advances in urban system science: Models and data. *PLOS One* 17(8). https://doi.org/10.1371/journal.pone.0272863

Artmann M (2015) Managing urban soil sealing in Munich and Leipzig (Germany) – From a wicked problem to clumsy solutions. *Land Use Policy* 46: 21-37. https://doi.org/10.1016/j.landusepol.2015.02.004

Barthelemy, M. (2019) The statistical physics of cities. *Nature Reviews Physics* 1: 406–415. https://doi.org/10.1038/s42254-019-0054-2

Behnisch M, Poglitsch H, Krüger T (2016) Soil sealing and the complex bundle of influential factors: Germany as a case study. *ISPRS International Journal of Geo-Information* 5: 132. https://doi.org/10.3390/ijgi5080132

Bergs R (2018) The detection of natural cities in the Netherlands: Nocturnal satellite imagery and Zipf's Law. *Review of Regional Research* 38(2): 111–140. https://doi.org/10.1007/s10037-018-0122-6

Bergs R (2021) Spatial dependence in the rank-size distribution of cities – weak but not negligible. *PLOS One* 16(2): e0246796. https://doi.org/10.1371/journal.pone.0246796

Bettencourt, LM, Lobo J, Helbing D, Kuhnert C, West G (2007) Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences of the United States of America* 104: 7301-7306. https://doi.org/10.1073/pnas.061017210

Bettencourt LM (2013) The origins of scaling in cities. Science 340(6139). https://doi.org/10.1126/science.1235823

Black D, Henderson JV (1999) A theory of urban growth. *Journal of Political Economy* 107(2): 252-284. https://doi.org/10.1086/250060

Brelsford C, Coon ET, Moran VE, Allan-Dumas M (2020) Urban scaling as validation for predictions of imperviousness from population. *Geophysical Research Letters* 47: e2020GL089742. https://doi.org/10.1029/2020GL089742

Broekel T, Knuepling L, Mewes L (2023) Boosting, sorting and complexity – Urban scaling and innovation around the world. *Journal of Economic Geography* 23(5): 979-1016. https://doi.org/10.1093/jeg/lbad006

Budde R, Neumann U (2019) The size ranking of cities in Germany: caught by a MAUP? *GeoJournal* 84: 1447-1464. https://doi.org/10.1007/s10708-018-9930-z

Butler RV, Maher MD (1982) The control of externalities in a growing urban economy. *Economic Inquiry* XX: 155-163. https://doi.org/10.1111/j.1465-7295.1982.tb01148.x

Cabrera-Arnau C, Prieto Curiel R, Bishop SR (2020) Uncovering the behaviour of road accidents in urban areas. *Royal Society Open Science* 7: 191739. https://doi.org/10.1098/rsos.19173

Correia CR, Roseland M (2022) Addressing negative externalities of urban development: Toward a more sustainable approach. *Urban Science* 6(38). https://doi.org/10.3390/urbansci6020038

Cottineau C, Hatna E, Arcaute E, Batty M (2016) Diverse cities or the systematic paradox of urban scaling laws. *Computers, Environment and Urban Systems* 63: 80-94 https://doi.org/10.1016/j.compenvurbsys.2016.04.006

Ewing R, Hamidi S (2015) Compactness versus sprawl: A review of recent evidence from the United States. *Journal of Planning Literature* 30(4): 413-432. https://doi.org/10.1177/0885412215595439

Fragkias M (2015) How can we apply complexity science to urban policy? UGEC Viewpoints blog (https://ugecviewpoints.worldpress.com/2015/08/27/) accessed 2 October, 2023

Fragkias M, Lobo J, Strumsky D, Seto KC (2013) Does size matter? Scaling of CO_2 emissions and US urban areas. *PLoS One* 8(6): e64727. https://doi.org/10.1371/journal.pone.0064727

Fujita M, Krugman P, Venables AJ (1999) The spatial economy: Cities, regions and international trade. Cambridge (Mass.): MIT Press

Gabaix X (2016) Power laws in economics: An introduction. *Journal of Economic Perspectives* 30(1): 185-206. https://doi.org/10.1257/jep.30.1.185

Harvey RO, Clark WAV (1965) The nature and economics of urban sprawl. *Land Economics* 41(1). https://www.jstor.org/stable/3144884

He B, Guo R, Li M, Jing Y, Zhao Z, Zhu W, Zhang C, Zhang C, Ma D (2023) The fractal or scaling perspective on progressively generated intra-urban clusters from street junctions. *International Journal of Digital Earth* 16(1): 1944-1961. https://doi.org/10.1080/17538947.2023.2218118

Henderson JV (1974) The sizes and types of cities. *American Economic Review* 64(4): 640-656. https://www.jstor.org/stable/1813316

Hesse M, Starke T, Jänchen I, Glinka P (2019) Prosperierende Städte, abgehängte Regionen? -Empirische Untersuchung zu Wirtschaft und Steuerkraft. *Wirtschaftsdienst* 2019. https://doi.org/10.1007/s10273-019-2517-6

Isard W (1956) Location and space economy. Cambridge (Mass.): MIT Press

Kaufmann T, Radaelli L, Bettencourt LM, Shmueli E (2022) Scaling of urban amenities: Generative statistics and implications for urban planning. *EPJ Data Science* 2022. https://doi.org/10.1140/epjds/s13688-022-00362-6

Krugman P (1991) Increasing returns and economic geography. *Journal of Political Economy* 99(3): 483-499. https://doi.org/10.1086/261763

Langer S, Korzhenevych A (2018) The effect of industrial and commercial land consumption on municipal tax revenue: Evidence from Bavaria. *Land Use Policy* 77: 279-287. https://doi.org/10.1016/j.landusepol.2018.05.052

Lefeber L (1957) Allocation in space: Production, transport and industrial location. Amsterdam: North Holland Publishing

Liu Z, Liu H, Lang W, Fang S, Chu C, He F (2022) Scaling law reveals unbalanced urban development in China. *Sustainable Cities and Society* 87: 104157. https://doi.org/10.1016/j.scs.2022.104157

Lobo J, Bettencourt LMA, Strumsky D, West GB (2013) Urban scaling and the production function of cities. *PLoS One* 8(3): e58407. https://doi.org/10.1371/journal.pone.0058407

Lösch A (1954) The economics of location. New Haven: Yale University Press

Ma Q, Wu J, He C, Hu G (2018) Spatial scaling of urban impervious surfaces across evolving landscapes: From cities to urban regions. *Landscape and Urban Planning* 175: 50-61. https://doi.org/10.1016/j.landurbplan.2018.03.010

Melo PC, Graham DJ, Noland RB (2009) A meta-analysis of estimates of urban agglomeration economies. *Regional Science and Urban Economics* 39: 332-342. https://doi.org/10.1016/j.regsciurbeco.2008.12.002

Ribeiro H, Oehlers M, Moreno-Monroy AI, Kropp J, Rybski D (2020) Association between population distribution and urban GDP scaling. *PLoS One* 16(1): e0245771. https://doi.org/10.1371/journal.pone. 0245771

Richardson HW (1977) The new urban economics: And alternatives. London: Pion

Rybski D, González M (2022) Cities as complex systems – Collection overview. *PLOS One* 17(2). https://doi.org/10.1371/journal.pone.0262964

Sarkar S, Arcaute E, Hatna E, Alizadeh T, Searle G, Batty M (2020) Evidence for localization and urbanization economies in urban scaling. *Royal Society Open Science* 7: 191638. https://doi.org/10.1098/rsos.191638

Seto KC, Güneralp B, Hutyra LR (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America* 109(40). https://doi.org/10.1073/pnas.1211658109

Strano E, Sood V (2016) Rich and Poor Cities in Europe: An Urban Scaling Approach to Mapping the European Economic Transition. *PLoS One* 11(8): e0159465. https://doi.org/10.1371/journal.pone. 0159465

Strohbach MW, Döring AO, Möck M, Sedrez M, Mumm O, Schneider AK, Weber S, Schröder B (2019) The "hidden urbanization“: Trends of impervious surface in low-density housing developments and resulting impacts on the water balance. *Frontiers in Environmental Science* 7:29. https://doi.org/10.3389/fenvs.2019.00029

Tuia D, Moser G, Wurm M, Taubenböck H (2017) Land use modeling in North Rhine-Westphalia with interaction and scaling laws. 2017 Joint Urban Remote Sensing Event (JURSE). https://doi.org/10.1109/JURSE.2017.7924542

Turner RK (2000) Markets and environmental quality. Clark G, Feldman MP, Gertler MS (eds) The Oxford Handbook of Economic Geography. Oxford and New York: Oxford University Press: 585-606

Webster C (2024) Tiebout, Coase and urban scaling. *Annals of Regional Science* 72 (online 27 April 2024). https://doi.org/10.1007/s00168-024-01272-3

Weitzman ML (1974) Prices vs. quantites. *Review of Economic Studies* 41(4): 477-491. https://doi.org/10.2307/2296698

Xiao Y, Gong P (2022) Removing spatial autocorrelation in urban scaling analysis. *Cities* 124: 103600. https://doi.org/10.1016/J.cities.2022.103600

Xu G, Zhu M, Chen B, Salem M, Xu Z, Li X, Jiao L, Gong P (2023) Settlement scaling law reveals population-land tensions in 7000+African urban agglomerations. *Habitat International* 142: 102954. https://doi.org/10.1016/j.habitatint.2023.102954

Ye L, Wu AM (2014) Urbanization, land development and land financing: Evidence from Chinese cities. *Journal of Urban Affairs* 36: 354-368. https://doi.org/10.1111/juaf.12105

Zünd D, Bettencourt LMA (2019) Growth and development in prefecture-level cities in China. PLoS One 14(9): e0221017. https://doi.org/ 10.1371/journal.pone.0221017