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REVIEW

How smart is smart growth? Examining the environmental validation behind city compaction

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Abstract Smart growth (SG) is widely adopted by planners and policy makers as an environmentally friendly way of building cities. In this paper, we analyze the environmental validity of the SG-approach based on a review of the scientific literature. We found a lack of proof of environmental gains, in combination with a great inconsistency in the measurements of different SG attributes. We found that a surprisingly limited number of studies have actually examined the environmental rationales behind SG, with 34% of those studies displaying negative environmental outcomes of SG. Based on the insights from the review, we propose that research within this context must first be founded in more advanced and consistent knowledge of geographic and spatial analyses. Second, it needs to a greater degree be based on a system's understanding of urban processes. Third, it needs to aim at making cities more resilient, e.g., against climate-change effects.

Keywords City compaction · City densification · Environmentally friendly urban development · Smart growth · Sustainable urban development

INTRODUCTION

Ever since the Neolithic revolution and the advent of agriculture, human conglomeration in towns and cities has provided immense benefits. However, urbanization is presently occurring at an unprecedented pace in history and has been deemed one of the key trends in the Anthropocene (Biermann et al. 2016). Continuing population growth and urbanization are projected to add 2.5 billion people to the world's urban population by 2050 (United Nations 2014), and it has been projected that by the year 2030, the global urban land cover will nearly have tripled in comparison to that in the year 2000 (Seto et al. 2012). In many cases, the pace of urban land development also far exceeds the rate of population growth, contributing to ineffective and unsustainable patterns of urban growth (i.e., sprawl) into suburbs and rural areas, resulting in low-density dispersal, automobile-dependent land-use patterns that contribute to air pollution and increased greenhouse gas emissions from transport (Angel et al. 2016), as well as to significant ecological impacts (McDonald et al. 2010; Colding 2011; Concepción et al. 2015). Many European cities, despite the decline in population growth, as well as in household numbers, still continue to spread, due to an increase in per capita space of living (Haase et al. 2013).

As a response to the ineffective and unsustainable patterns of urban growth (sprawl), concepts revolving around compaction has emerged, such as *compact cities* and *smart growth* (SG). The introduction of the term *compact city*, in the context of influencing urban planning, can be attributed to Jacobs (1961), mainly as a response to counter the reduction of density of dwellings in urban areas. Although coined in America, this concept is today more often used in a European (e.g., European Commission 2013), particularly British (e.g., Garland 2016) context, while *SG,* often fused under the heading *New urbanism, or Transit-oriented development* (Frumkin et al. 2004), is more often used in a North American context. These umbrella concepts represent the most prevalent planning strategies to combat urban sprawl, advocating and embracing compact, transit-oriented, walkable, and bicycle-friendly land use that include mixed-use development with a range of housing choices. A

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dominant feature of these umbrella design-based strategies involves compact urban form (i.e., densification) and the strategy to locate new developments within already built-up areas, encouraging infill-development and redevelopment of older facilities and brownfields. Although we include both of these essential concepts in our search algorithm (see, section on "Materials and methods") and view them, for our purpose, as being similar enough to be used interchangeably, we will, for simplicity, here on, refer to the congregation of the features described above as SG. We choose the term SG as it, somewhat controversially implicitly emphasizes that growth is inherently something good, and, also, since it recently, increasingly often, has been linked to the controversial concept *Smart City* (Colding and Barthel 2017). The SG-approach aims at safeguarding against more remotely located ecosystems being transformed into urban fringe development, which threatens prime farmlands, wetlands, and unique wildlife habitat (Litman 2009). Based on the above assertions, SG is widely adopted by urban planners and policy makers as the most environmentally friendly form of building cities (Buys and Miller 2012). An expression of this is that it is frequently endorsed in European national and local policy documents (Howley 2010). Also, the European Commission's Green Paper (European Commission 2013), the UN-Habitat (2012), and the UN-supported Millennium Ecosystem Assessment argued that city compaction is the most environmentally benign strategy for building cities (MA 2005), primarily in the environmental context of combating climate change through mitigating CO_2 emissions. The European Commission has also identified noise as a troublesome pollution, which can be mitigated by a combination of strategies, including urban planning, to, e.g., reduce noise from traffic (European Commission 2002). The strategy is also receiving support from the American EPA (EPA 2017), claiming environmental gains, e.g., in the context of preserving natural lands and critical environmental areas and protecting water and air quality.

However, conclusive proof of the effectiveness of SG-approaches for delivering on the environmental benefits is lacking. For exemple, while some studies show that SG is effective when it comes to climate-change mitigation (e.g., Newman and Kenworthy 1989; Stone et al. 2007), other studies yield different, quite contradictory results (e.g., Handy 2005; Holden and Linnerud 2011). Other researchers claim that the SG-approach has focused too much on climate-change *mitigation*, and not paid enough attention to climate-change *adaptation* (Blanco et al. 2009). This point is important to consider as urban climate responses are particularly vulnerable to the inertia built into certain technologies, infrastructures, institutions, and behavioral norms, which in turn can create path dependencies that constrain the effectiveness of mitigation or adaptation actions in cities (Ürge-Vorsatz et al. 2018). Furthermore, the SG-approach has also been criticized based on the lack of knowledge as to what extent and in what ways SG, in the context of the attractiveness of city center living, outweighs perceived negative outcomes, e.g., regarding residential preferences and housing satisfaction (Howley 2010).

The purpose of this paper is to bring clarity into the *environmental* validity of the SG-approach by examining the underlying scientific evidence. Hence, we conducted a large-scale scientific literature review on the environmental claims behind the SG-approach. Previous reviews on SG have been conducted (van der Waals 2000; Ye et al. 2005; Ahlfeldt and Pietrostefani 2017). However, to the best of our knowledge, this is the first time an international review with a specific environmental focus—entailing a detailed analysis of how different SG attributes are measured, as well as addressing the issue of scales—has been performed.

MATERIALS AND METHODS

An international scientific literature review on SG was conducted through a systematic search for scientific publications using the Scopus and Web of Knowledge databases. Only publications in English and within the subject areas as environmental sciences and social sciences were included. To limit reviews to more updated cases, the search included only entries available from January 1985 to May 2017. The publications were selected using the following keywords: "smart growth" or "compact city" (see, motivation for these choices in the introduction) AND "natural environment" or "ecosystems" or "ecosystem services" or "natural systems" or "biodiversity" or "biological diversity" or "green spaces" or "green urban space" or "green structure" or "climate" or "nature" AND "quantitative" or "empirical" or "data." We base the inclusion of the term *natural*, as in *natural environment* and *natural systems* based on the concept of natural capital (Costanza and Daily 1992), with the aim of introducing the value of nature into the world of economics by viewing nature as a form of capital. On that same note, the concepts of *ecosystems* and *ecosystem services* (Daily 1997) are also included. The concept *biological diversity*, or *biodiversity* for short, is illuminated as a prerequisite for underpinning both the concepts of ecosystem services as well as the work of nature (Baskin 1998). The inclusion of terms related to the word *green*, such as *green space*, *green urban space*, and *green structure* is based on the vast literature assessing the benefits of green areas for the human population in urban areas (e.g., Hartig et al. 2014). *Climate* is included based on the suggested strong connection between SG and climate (e.g., Newman and Kenworthy 1989). Inclusion of the term *nature* is derived from the standpoint that the work of nature is essential for underpinning human well-being and survival (Baskin 1998). One of the authors behind this paper did an initial screening of titles and abstracts to eliminate irrelevant articles.

In the next step, titles and abstracts were screened to determine which articles to accept for full review. This was followed by reading the selected articles that were divided among the four authors of this paper, and a series of five discussion seminars were held amongst the reviewers. The initial search for articles yielded 150 articles for abstract screening. Inclusion or exclusion of an article was based on predefined criteria as follows: (i) environmental issues addressed; and (ii) the empirical evidence behind findings. Exclusion criteria were (i) whether the article's focus is primarily on socioeconomic issues (e.g., social cohesion, social equity, housing affordability); (ii) whether it is the article, a review, or policy article, i.e., it does not entail empirical evidence? After the initial abstract screening, 105 articles were selected for full article screening, using the above-described criteria, resulting in 29 articles used for the review (see Electronic Supplementary Material).

An initial round of data was deduced from the 29 articles, including year of publication, geographic location of the empirical data used in the article, scale(s) addressed (micro—at the level of individual buildings; meso—at the block- and neighborhood levels; and macro—at the level of a city), techniques for measuring SG, and primary results concerning the relation between SG and environmental performance. To be able to determine and elaborate on the scientific evidence of SG in relation to environmental issues, it is necessary to identify and measure the phenomenon of SG in a consistent manner in order to determine whether one is dealing with the same phenomenon in different studies or not. To resolve this, we assessed three key areas of how SG is dealt with in the 29 articles under review (see, Electronic Supplementary Material for a numbered list of the 29 articles included in the review): (1) the *definition* of SG, (2) identification of characteristic *attributes* of SG, and (3) techniques for *measurements* of such attributes. We deal with each of the key areas assessed in the following discussion.

RESULTS

A first screening of the articles showed a steady increase of publications since 1999. Over 30% of the articles were studies derived from the USA, followed by China (28%), and the UK and Canada (10% each). Other countries in which one study each had been conducted were Italy, Germany, the Netherlands, Norway, Denmark, Australia, and India.

Definitions

Our review shows that there is little agreement on what SG actually stands for and how it is defined in the articles. The concept is generally presented in broad terms; for instance, "Smart growth is a set of principles for guiding development of healthy, vibrant communities characterized by a sense of place" (Almanza et al. 2012); "designed to increase the density, mix, and pedestrian and transit orientation of urban development" (Stone et al. 2007); "compact, pedestrian-scaled urban form to achieve an environmental objective" (Calthorp 1993; Stone and Rodgers 2001); multiple and intensive land-use development, with housing, infrastructural services, and amenities in proximity to each other (Lau et al. 2011). Moreover, because the SG-concept has evolved as a critical reaction to urban sprawl, six of the reviewed articles simply defined SG as the opposite of sprawl (Pauleit and Golding 2005; Pauleit et al. 2005; Stone 2008; Stone et al. 2010; Liu et al. 2012; Salvati et al. 2012), which in turn could be defined in such broad and jargon-like definitions: "decentralized land use patterns characterized by low population densities and auto-oriented design schemes" (Stone 2008). In conclusion, there is no generally agreed upon definition of SG, rather a broad number of descriptions exists, varying around certain themes.

Attributes

Certain reoccurring *attributes*, central to SG concerning its environmental performance, are found. These include *density*, e.g., population density, built density; *land use/cover*, including land use [mix]; *urban form,* e.g., building types, urban layout, shape of cities; *accessibility*, e.g., closeness, street connectivity; and *composite*, a sprawl index, including centeredness, street network density, population density, accessibility of residential uses to nonresidential uses, and mix of land uses (see Table 1).

Density, with 20 articles is by far the most commonly used attribute, followed by land cover/use with 12 articles, urban form with 7 articles, accessibility with 4 articles, and composite with 2 articles.

Further, we found a distinct branching among the articles analyzed, which largely represents three types of topics commonly addressed. First, the majority of articles deal with transportation and air pollution (e.g., CO_2 and SO_2 emissions), where not only the variations in density of cities are deemed central, but also the land cover and accessibility. Second, many studies revolve around the quality of urban life, i.e., walking and cycling versus car use, air quality, and microclimatic conditions in cities (i.e., heat effects). In this group of articles, many references to density are typically found, but also to land cover,

Table 1 Number of articles and article ID (see, Electronic Supplementary Material for a numbered list of articles included in the review) linked to the different identified Smart Growth measures. Multiple Smart Growth measures can be applied within a single article

Smart growth measures	Number of articles	Article ID #
Density	20	1,3,4–13,16,17,19,21,22,24,27,28
Population density (e.g., residential density, population density, per capita land consumption, ratio of jobs to population, population growth)	18	3,4–6,8–13,16,17,19,21,22,24,27,28
Commercial density (e.g., employment density, business density, sale density)	2	6,8
Physical density (e.g., building density, plot ratio, housing density, neighborhood density)	5	1,7,8,17,21
Perceived density (e.g., crowding of buildings, crowding of people, crowding within buildings)	1	10
Land use/land cover	12	2,4,7,9,14,15,18,20,22,23,25,26
Land cover (e.g., area of built (sealed) land cover, area of natural (vegetated) land cover, tree canopy, density of vegetation, surface albedo)	8	2,7,14,15,18,20,23,25
Land use (e.g., residential area ratio)	5	4,9,20,22,26
Urban form	7	3,7,8,12,18,26,29
City form (e.g., form ratio, compactness ratio, elongation ratio)	2	3,29
Street layout (e.g., % of 4-way intersections, street network density)	4	8,18,26,29
Urban block form (e.g., height to floor area ratio, height to depth street block, sky view factor, block size, size of heat sink)	3	7,8,12
Accessibility	4	4,9,12,26
Accessibility (e.g., access to private yards, accessibility of residential uses to nonresidential uses)	3	4,9,12
Proximity (e.g., distance to city center/local center, centeredness)	4	4,9,12,26
Composite	2	9,12
Sprawl index (including centeredness, street network density, population density, accessibility of residential uses to nonresidential uses and mix of land uses)		

especially in relation to urban heat island effects. A third group of papers discusses general growth, dispersion, and sprawl of cities, and how these may lead to a change from natural or agricultural land to urban land uses and a loss of biodiversity. Again density is central, followed by land cover. Two specific frameworks for identifying SG attributes, as well as techniques for their measurement, are illuminated in some of the reviewed articles. First, the *3D-concept* (Cervero and Kockelman 1997), later augmented with a fourth D, where the D's stand for density, diversity, design, and destinations, in which diversity relates directly to the attribute land cover, design to the attribute urban form and where destinations has strong similarities with the attribute accessibility. Second, the *Sprawl index* (Ewing et al. 2003), used in two articles, which has many similarities to the 3D-concept, where we find the following criteria: centeredness, connectivity, density, and land-use mix.

Measurements of attributes

At closer inspection, an attribute, such as *density*, can refer to different entities and can also be measured quite differently. For instance, as stated before, there is reference to measures of density found in 20 of the articles distributed between population density, commercial density, physical or built density, and perceived density. Moreover, the same measure, for instance population density, is used differently in different articles. This is primarily due to the fact that the resolution of the measurement varies; it sometimes denotes to the population density of the urbanized land of a whole city, to census areas, or to building blocks. It also varies concerning how population is defined, variously referred to as households, residents, or total population (residents and working population together). Similar inconsistencies in measurement are also found in reference to the criteria of *land cover/land use*, varying between, e.g., area of built (sealed) land cover, density of vegetation, surface albedo, and residential area ratio; *urban form*, varying between, e.g., form ratio, street network density, height-to-floor area ratio and block size; and *accessibility*, varying between, e.g., accessibility to private yards, vicinity to green/water, and centeredness (degree of mono- or polycentrism). Hence, we found great inconsistency in the way attributes are measured (Table 1) and a lack in proficiency in geospatial analysis in the SG discourse—an aspect often overlooked or treated superficially in the literature.

Identified environmental arguments

Based on the literature review of the 29 articles, five different environmental arguments could be identified: *greenhouse gas emission*, *air quality*, *biodiversity*, *urban heat island*, and *open space* (Fig. 1).

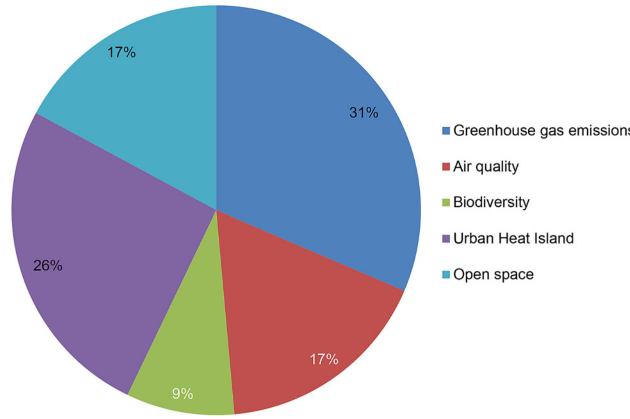

Fig. 1 Percentage of articles within each of the five environmental arguments addressed in the 29 reviewed articles. Article IDs for *greenhouse gas emission*; *air quality*; *biodiversity*; *urban heat island*; and *open space*. See, Electronic Supplementary Material for a numbered list of review references

In 17 of the articles, positive environmental effects related to SG were found, ten found negative effects, and two articles found positive effects up to a certain level of compactness, after which the effect became negative. The number of SG measures and scales in relation to the different environmental arguments were also quantified (Table 2).

Six articles addressed the topic "less car use and more public transport under SG," focusing on the environmental gain of reducing CO_2 emissions, i.e., the environmental benefit of reduced *greenhouse gas emission*. These six articles were based on studies conducted on several different spatial scales (micro, meso, macro), focusing on the everyday travel patterns of city inhabitants. Although it is convincingly shown that a compact city structure indeed causes lower energy consumption of everyday travel, even after accounting for self-selection bias (e.g., Cao et al. 2009), only one article examined the effect that the compact city strategy has on leisure travel. When including leisure trips Holden and Linnerud (2011) found that policies aimed at reducing energy consumption and CO_2 emissions for everyday travel may actually have the opposite effect on leisure travel.

Another important environmental benefit associated with compact cities is *air quality* improvement. Two of the reviewed articles, focusing on the macroscale in the US, showed a positive effect of densification of cities and improved air quality. However, a study of eleven neighborhoods at the microscale in Mumbai metropolitan region, India, found that improved air quality was in fact negatively correlated with high-density development. This study also differed from the two US studies in initial city

Table 2 Number of articles addressing different environmental argument linked to smart growth according to pro–con smart growth, smart growth measures, and scales. Some articles address multiple environmental arguments, SG measures, and scales

	Environmental argument				
	Green house gas emission	Air quality	Biodiversity	Urban heat island	Open space
Pro/con SG					
Pro SG	7	6*	0	5	6*
Con SG	4	2*	3	4	2*
SG measure					
Density	9	5	0	2	4
Land cover	1	0	1	8	0
Urban form	2	2	0	2	0
Accessibility	1	1	0	1	1
Composite	0	1	0	1	0
Scales					
Micro	3	0	1	3	1
Meso	5	1	2	6	1
Macro	7	5	0	4	5

*Two articles (see Electronic Supplementary Material) identify a tipping point. Before the tipping point, the link between smart growth and the environmental benefit is positive, but above a certain density, it becomes negative. Hence, these two articles contribute to both the pro-SG and the con-SG columns

density. Studies that support the notion of improved air quality are, thus, not only few, but also contradictory, and the issues of scale and discrepancies in initial densities, which exist between the developed and the developing cities, have yet to be resolved before conclusions can be drawn on the impact of compactness on air-quality improvements.

Biodiversity is yet a third environmental indicator addressed in the reviewed articles. Only three articles addressed this indicator, all showing negative correlation between biodiversity and increased urban density.

The ability to mitigate the *urban heat island* effect (UHI) and extreme heat events (EHEs) is another benefit addressed in the examined articles. It is especially relevant in the context of climate change. Nine articles addressed this issue, six were positive toward SG and three were negative. Of the pro articles two were grounded in an American anti-sprawl context and both asserted that the UHI effects and EHEs are more effectively mitigated in the denser-city core areas of metropolitan regions than in the suburbs and the sprawling parts. Stone et al. (2010), for example, concluded that the design and management of land use in metropolitan regions may thus provide a tool for mitigation. However, they also found that the rate of deforestation in the most sprawling metropolitan regions is more than double the rate in the most compact metropolitan regions.

Saving *open space* by building dense is yet another environmental indicator addressed in our reviewed sample, which was assessed in six articles. Two of the articles were anti-sprawl, based on the environmental benefits of SG as a way of saving open space. McDonald et al. (2010, p. 1) defined open space as “agricultural land and more natural land-cover, such as forest and grassland, including both remnant patches within a city as well as larger patches at the city’s fringe.” Salvati et al. (2012) describe the compact growth of Mediterranean cities as involving primarily poor-quality land, such as pastures, abandoned fields, and low-intensity agricultural areas, thus potentially mitigating the observed and troublesome disappearance of rural land (including forests, arable lands, pastures, and vineyards). Almanza et al. (2012) takes a different approach, and focus on the importance of greenness as an aspect of community design, related to several SG principles, such as walkability, mixed land use, and sense of place. They found that children who experienced > 20 min of daily exposure to green spaces engaged in nearly 5 times the daily rate of moderate to vigorous physical activity compared to children with nearly zero daily exposure to green spaces and that this association was stronger for residents in “smart growth” neighborhoods compared to conventional neighborhoods. Almanza et al. (2012) thus also included urban greenness in “open space” and illuminate the importance of including greenness in SG principles when designing urban neighborhoods.

When assessing the consistency across the reviewed articles it is clear that not only do the majority of the articles (62%, i.e., 18 articles) include population density as the attribute measurement of choice, but that out of the 8 groups lumping comparable articles, as much as 5 use population density (Table 3).

DISCUSSION

Scrutinizing the environmental gains of SG

A number of influential supra-national bodies and organizations, like UNEP and the EU, have launched city compaction as an environmental benign strategy of building cities. However, based on the results from this review, this claim is not based on solid scientific grounds. In fact, a surprisingly limited number of studies have actually examined the relationship between SG and the environment and, among those, as much as 34% found negative environmental outcomes in relation to SG. The studies that do show positive relationships do so based on a restricted

Table 3 The consistency across the reviewed articles is presented by assessing which articles that are comparable in connection to the five different environmental arguments, type of measurement and scales. The percentage of articles that are pro-SG within the different comparable groups is also included. PD = population density, LC = land cover

Environmental argument	Tot. no. of articles	Measurement/ scale	No. articles	Pro-SG %
Greenhouse gas emissions	11	PD/macro	7	57
Greenhouse gas emissions	11	PD/micro	3	67
Air quality	6	PD/macro	4	75/50*
Biodiversity	3	LC/meso	2	0
Urban heat island	9	PD/micro	3	67
Urban heat island	9	LC/meso	5	40
Urban heat island	9	LC/macro	2	100
Open space	6	PD/macro	3	100/67*

*Article within which a tipping point is identified is included. The higher percentage is before the tipping point has been crossed and the lower percentage after

number of environmental parameters, mainly confined to the mitigation of CO_2 emissions by reduced private transportation. However, the majority of these studies suffer from a lack of a broader analytic systems perspective, not taking into account important parameters such as leisure travel, which may turn out to be a game changer (Holden and Linnerud 2011), thus still leaving us uninformed even about the environmental gains that a compact-city structure offers in the context of reducing CO_2 emissions. Moreover, only three articles in our review sample addressed the important relationship of biodiversity and city compaction, despite the high species-extinction rate witnessed on Earth today (DeVos et al. 2015; WWF 2017). What is even more serious is that these articles all showed negative links between biodiversity and city compaction. However, according to UNEP (Alcamo and Leonard 2012) compactness should also be accompanied by mixed-use settlement patterns and urban greening to boost urban sustainability and resilience, of which biodiversity is an essential part. But how this should be achieved is not addressed, or is the issue of how much greening is needed, where, what type, and on which scales? The answers will, of course, differ, depending on which species we are trying to conserve (e.g., Jansson and Polasky 2010; Zetterberg 2011). Also, building on the idea that clustering different combinations of land uses in urban green areas could create interactions that support biodiversity (Colding 2007) again shows the potential of applying a systems approach.

In the context of mitigating UHI effects and EHEs, although two-thirds of the articles addressing these issues were pro-SG, Stone et al. (2010) observed great discrepancies between the rate of deforestation in the most sprawling metropolitan regions and the most compact metropolitan regions. With the existing knowledge of the great importance of plants, especially trees, for temperature mitigation (Hough 2004), a relevant question would be this: What is the potential of sprawling metropolitan regions to also act as a tool for mitigation, when using appropriate design and management strategies?

While important parameters such as air quality, biodiversity, and open-space conservation have been measured, there are yet a number of other critical parameters that largely have been neglected in the SG literature, such as noise—despite this parameter being specifically targeted by the European Commission (2002); and ecosystem functions, such as pollination, despite the potential link between pollination potential and the design of dense urban areas (Berghauser-Pont et al. 2018; Stange et al. 2018a, b). Also, although limiting the effects of UHIs potentially constitutes a constructive adaptation strategy against negative climate-change effects, the major focus within SG is still overwhelmingly on mitigation strategies, such as the limiting of CO_2 emissions (Blanco et al. 2009), which is also reflected in the articles reviewed here (Fig. 1). Considering that humanity is on the verge of crossing thresholds that likely will trigger nonlinear planetary-scale effects (Rockström et al. 2009) and that cities are highly vulnerable in this context (Pachauri and Meyer 2014), it is clear that one can not focus only on decarbonizing cities when implementing the 2015 Paris Climate Agreement (Figueres et al. 2017), but one needs equally as well to focus on making cities more resilient against climate-change effects.

The paradoxes in measuring SG

As also evident from our literature review, the SG-approach is associated with several limitations, mainly due to the way SG attributes are measured, which makes it awkward to determine its environmental pros and cons. We are dealing with a phenomenon that lacks a common overarching definition, but instead is defined by the use of a set of fairly consistent and reoccurring attributes. However, there is great inconsistency when it comes to the measurement of some of these attributes, as mentioned earlier. Unfortunately, population density, the most commonly used SG attribute, shows so much variation in how it is measured (Table 1) that it is difficult to know which studies are truly comparable to each other. The main problems identified regard the definition of area boundaries and the aggregation level at which the attributes are measured. These two issues

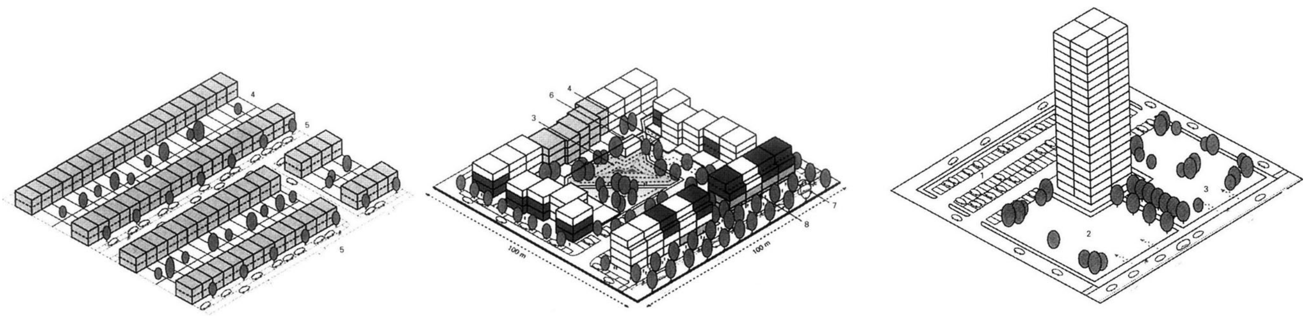

Fig. 2 Three areas with 75 dwellings per hectare (Fernandez Per and Mozas 2004)

are a consequence of what in physical geography is described as the modifiable areal unit problem (MAUP) and is not limited to the discussion on density, but relates to all SG attributes (Openshaw and Taylor 1979). The main issue of concern related to MAUP that is not or only briefly discussed in the SG literature is the scale effect, which is attributed to variation in numerical results, owing strictly to the number of areal units used in the analysis of a given area. The larger the area of aggregation and the greater the diversity in the aggregated parts of that area—the more the variation is lost in the calculation and the more the abstract and the less relevant the result is for urban planning and design (De Jong and van Der Voordt 2002).

Further, as SG is widely adopted by urban planners and policy makers as the most environmentally friendly form of building cities, the measurements used should be informative for urban planners and policy makers. Critics to the use of density in urban planning and design have argued that the use of population density for anything but statistical purposes is questionable, as it is a too elastic concept that poorly reflects urban qualities (Fig. 2). Forsyth (2003) cautions us not to confuse density with building type and assume that, for example, detached houses have a lower density than attached housing types. These distinct differences in urban qualities cannot be captured solely with the rather crude density measure of population density.

It is important to note that the physical city works like a medium, structuring and shaping environmental processes in cities, and is therefore, an essential tool for restructuring such processes into more sustainable trajectories. However, if we in research measure density as population density, the results are not directly applicable in practice, since population density is something that typically varies over time and is not something that can be directly influenced in urban planning and design. Measuring *physical density* (Alexander 1993), on the other hand, is directly related to urban planning and design, especially when it includes various metrics such as built intensity, ground coverage, building height, and accessibility as proposed by Berghauser-Pont and Marcus (2010, 2014).

This hypothesis highlights two of the basic paradoxes in measuring SG, the "density paradox" and the "modifiable areal unit problem," which deserve greater attention by researchers.

CONCLUSIONS

The lack of proof of environmental gains, in combination with the identified great inconsistency in the measurements of different SG attributes and the disparity of scales, suggests that the currently most prevalent planning strategy for sustainable urban development, SG, lack sufficient scientific foundations and that few if any of the current 'truths' about compaction and environmental gains can be substantiated. It is an unfortunate time in history to be found lacking in knowledge on this topic—why the aim here is not to debunk SG—but to argue for the need to set research on sustainable urban planning on firmer grounds. Based on the review, three vital issues in this respect are identified. Research in this direction must, *first*, to a greater degree, be based in a systems understanding of urban processes; *second,* aim toward making cities more resilient, e.g., against climate-change effects; and *third*, be founded in more advanced knowledge and consistent use of geospatial analysis.

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