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The economic effects of density: A synthesis☆

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ABSTRACT

This paper synthesises the state of knowledge on the economic effects of density. We consider 347 estimates of density elasticities of a broad range of outcomes ranging from wages, innovation, rents, various amenities, the cost of providing public services, transport- and environment-related outcomes to health and wellbeing. More than 100 of these estimates have not been previously published and have been provided by authors on request or inferred from published results in auxiliary analyses. We contribute original estimates of density elasticities of 16 distinct outcome variables that belong to categories where the evidence base is thin, inconsistent or non-existent. Along with a critical discussion of the quality and the quantity of the evidence base we present a set of recommended elasticities. Applying them to a scenario that roughly corresponds to an average high-income city, we find that density seems to be a net-amenity that is associated with positive external welfare effects. Densification policies may be welfare enhancing, but the distributional effects may be regressive, especially if residents are immobile and housing supply is inelastic.

1. Introduction

The degree of concentration of economic activity in urban areas is striking as they host more than 50% of the world's population (United Nations, 2014) on only an approximate 2.7% of the world's land (GRUMP, 2010; Liu et al., 2014).[2] There is a consensus among planners and policymakers, however, that even higher densities within cities and urban areas are desirable, at least on average (Boyko and Cooper, 2011; OECD, 2012). Most countries pursue policies that implicitly or explicitly aim at promoting "compact urban form", reflecting the concern that unregulated economic markets will fail to deliver allocations of uses and infrastructure that are efficient and equitable (IAU-IDF, 2012; Holman et al., 2014). It is difficult to ascertain, however, to what extent this normative statement prevailing in the policy debate can be substantiated by evidence (Neuman, 2005).

To our knowledge, no attempt has been made to synthesise the evidence on the economic effects of density and to compare the variety of costs and benefits across a comprehensive range of outcome categories. It seems fair to state that the dominating "compact city" policy paradigm, which aims at shaping the habitat of the urban population over the decades to come, is not well-grounded in evidence. We make four contributions to address this notable gap in the literature.

Our first contribution is to provide a unique summary of the quantitative literature on the economic effects of density. Our evidence base contains 347 estimates (from 180 studies) of the effects of density on a wide range of outcomes including accessibility (job accessibility, accessibility of private and public services), various economic outcomes (productivity, innovation, value of space), various environmental outcomes (open space preservation and biodiversity, pollution reduction,

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[2] The estimates of the global urban land reported in the literature vary widely, from less than 0.3 to 3% primarily because of the different definitions of urban land and data used (night light data, Landsat data etc.) (Angel et al., 2005; GRUMP 2010; Liu et al., 2014). In 2010, the global urban land was close to 3%, while the global built-up area was approximately 0.65%.

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energy efficiency), efficiency of public service delivery, health, safety, social equity, transport (ease of traffic flow, sustainable mode choice), and self-reported well-being.

While the evidence base is shared with a companion paper (Ahlfeldt and Pietrostefani, 2017), the results presented in the two papers are mutually exclusive. In the companion paper, we analyse the effects of a variety of compact city characteristics (including morphological features and land use mix), restricting the interpretation to qualitative results in order to explore the full evidence base. In this paper, we focus on a quantitative comparison, and, therefore, restrict the analysis to results that can be expressed as density elasticity estimates. For more than 100 cases, we conduct back-of-the-envelope calculations to convert the results into a comparable metric or obtain results that had not previously been published from the relevant authors. Borrowing techniques from meta-analytic research, we analyse within-category heterogeneity with respect to characteristics such as the methods used, the citations adjusted for years since publication, or the geographic setting of the analysis. In some instances, we make admittedly ambitious assumptions to translate results published in fields such as engineering and medical research into a format that is compatible with the conventions in economics and related disciplines.

Our second contribution is to provide original elasticity estimates where the evidence base is thin or inconsistent. We provide transparent density elasticity estimates based on a consistent econometric framework and OECD data that refer to 16 distinct outcome variables (from 10 outcome categories). For some outcomes, such as the density elasticity of preserved green space, our estimates are without precedent. We provide an estimate of the elasticity of density with respect to city size, which facilitates a better comparison of the results from studies analysing the effects of density and city size. To reconcile the evidence on the effects of density on wages, rents, and various (dis)amenities, we also provide novel estimates of the density elasticity of construction costs.

Our third contribution is to condense this broad evidence base into a set of 15 category-specific density elasticity estimates. Specific to each category, we either recommend the weighted (by adjusted citations) mean across the elasticity estimates in our evidence base, an estimate from a high-quality original research paper or one of our original estimates. Along with the recommended elasticities, we provide a critical discussion of the quality and the quantity of the evidence base, highlighting priority areas for further research. The compact presentation of a variety of density elasticity estimates in a consistent format is unique in terms of accessibility and coverage and represents a convenient source for research engaging with the quantitative interpretation of density effects.

Our fourth contribution is to monetise the economic effects of density. For each of the 15 outcome categories, we compute the per capita present value (PV, at a 5% discount rate) of the effect of a 1% increase in density for a scenario that roughly corresponds to an average metropolitan area in a developed country. For this purpose, we combine our recommended density elasticity estimates with several valuations of non-marketed goods such as time, crime and mortality risk, or pollution, among many others. The monetary equivalents allow for a novel accounting of the costs and benefits of density and how the net effect of density across a broad range of amenity and dis-amenity categories aligns with estimates of quality of life based on cost-earning differentials.[3]

Our analysis reveals sizeable benefits and costs of density. A log-point increase in density leads to (log-point effects in parenthesis) higher wages (0.04), higher rent (0.15) and lower average vehicle mileage (0.06), but also higher pollution concentration (0.13) and lower average speed (0.12). For other outcomes, existing estimates are better interpreted as associations in the data since the causal interpretation would rest on the strong assumption that differences in density are historically determined by factors that have no contemporaneous effects on outcomes. A log-point increase in density is associated with (log-point effects in parenthesis) higher patent activity (0.21), consumption variety value (0.12), preservation of green spaces (0.28), as well as lower car use (0.05), energy consumption (0.07), crime (0.085), and costs of providing local public services (0.17). Density, however, is also associated with higher construction costs (0.55), skill wage gaps (0.035), mortality risk (0.09) as well as lower self-reported well-being (0.004).

Studies that are more frequently cited, or use more rigorous methods, find less positive density effects (in a normative sense). The estimates also become less positive over time, possibly reflecting a trend towards the application of more rigorous methods. Although more evidence would be desirable to substantiate our findings, our analysis reveals some insights into geographic heterogeneity in density elasticity estimates. For non-high-income countries, the estimated density elasticity of wages, at 0.08, is twice as large for high-income countries, on average. Mode choice is less likely to change with density, whereas the gains from density in terms of domestic energy consumption appear to be larger. Compared to other developed countries, density in the US is associated with larger skill wage gaps and higher rather than lower crime rates. Our review of the literature also suggests that the effect of density on rents may not be log-linear. Estimates of the density elasticity of rent increase by 0.063 for every increase in population density by 1000 inhabitants per square kilometre. We do not find a similar non-linearity in the estimated effects of density on wages, suggesting that convex costs lead to a bell-shaped net-agglomeration benefits curve (Henderson, 1974).

In our illustrative scenario, a 1% increase in density leads to an increase in the per capita present value (infinite horizon, 5% discount rate) of wages and rents of \$280 (\$190 after taxes) and \$347. Summing up the monetary equivalents of all amenity and dis-amenity categories we find a clearly positive value, which is, however, not as large as the "compensating differential" (rent effect – after-tax wage effect). While density seems to be a net amenity, our admittedly imperfect accounting also suggests that part of the rent increase may be attributable to the higher cost of providing space in addition to enjoyable amenities. Policy-induced densification may lead to aggregate welfare gains. However, there may be a collateral net-cost to renters and first-time buyers.[4] This effect adds to a potentially regressive distributional impact due to a widening skill wage gap.

Our analysis unifies important strands in the economics literature on the spatial organisation of economic activity. We provide an explicit comparison of the magnitude of agglomeration benefits on the production (e.g. Combes et al., 2012) and consumption side (e.g. Couture, 2016), the effects of urban form on innovation (e.g. Carlino et al., 2007), housing rent (e.g. Combes et al., 2018), quality of life (e.g. Albouy and Lue, 2015), driving distances (Duranton and Turner, 2018), road speeds (Couture et al., 2018), public spending reduction (e.g. Hortas-Rico and Sole-Olle, 2010), energy consumption (Glaeser and Kahn 2010), skill-wage gaps (Baum-Snow and Pavan, 2012) and self-reported well-being (Glaeser et al., 2016), in addition to a range of density effects on outcomes that have remained under-researched in the economics literature. Our findings also have important policy implications as they suggest that densification policies are likely efficient but not necessarily equitable.

Some words are due on the limitations of this ambitious synthesis. The fundamental challenge the literature faces is to separate the effects of density from unobserved factors that determine density. As mentioned above, a causal interpretation often requires the strong identifying assumption that contemporary density is not endogenous to factors

[3] The indirect inference of quality of life from relative wages goes back to the work pioneered by Rosen (1979) and Roback (1982) which has spurred a growing literature (see Albouy & Lue 2015 for a review).

[4] To be theoretically consistent this interpretation requires that residents are not fully mobile (e.g. because they have location-specific preferences).

Table 1
Variation in density.

	(1) FUA, Non-US OECD data Pop. Density		(2) FUA, US OECD data Pop. density		(3) FUA, US Census data Pop. Density (PD)		(4) Census tract, US Census data Tract PD - FUA mean	
	Level	Ln	Level	Ln	Level	Ln	Level	Ln
Min	36	3.58	27	3.29	34	3.54	−1947	−10.99
p1	55	4.01	27	3.29	34	3.54	−1201	−3.18
p25	330	5.80	100	4.60	163	5.10	369	0.57
p50	580	6.36	179	5.19	371	5.92	1295	1.44
p75	994	6.90	386	5.96	648	6.47	2831	2.37
p99	4652	8.44	1661	7.42	1947	7.57	31,388	4.28
Max	4851	8.49	1661	7.42	1947	7.57	209,187	5.87
Mean	814	6.33	274	5.23	451	5.76	2907	1.36
SD[1]	798	0.90	268	0.89	370	0.90	5890	1.49
CV[2]	98.03%	–	97.81%	–	82.06%	–	202.58%	–
N	211		70		70		34,123	

Notes: Population density in inhabitants per square kilometre. Functional urban area (FUA) data from OECD (Columns 1 and 2). Census data matched to FUA shapefiles on GIS, aggregated to FUA (Columns 3 and 4) – data includes only core FUA, excluding the commuting zones around them. City cores are defined using the population grid from the global dataset Landscan (2000).

[1] Standard Deviation.

[2] Coefficient of variation.

that have direct effects on outcomes. Moreover, for individual-, firm-, and unit-based outcomes (e.g. wages, innovation, rent, wellbeing), the collected density elasticity estimates often capture composition effects. In general, the quantitative results are best suited for an evaluation of the effects of densification policies applied to individual cities (as opposed to all cities in a country) in the long run. Compared to wages and mode choice, the evidence base for the other outcomes is generally underdeveloped. While for some categories selected high-quality contributions are available, the nature of the evidence is at best preliminary for others. Significant uncertainty surrounds any quantitative interpretation in the categories urban green, income inequality, health, and well-being. We view these outcomes as priority areas for further research into the effects of density. In general, the extant evidence base consists of point estimates, so that heterogeneity in density effects across contexts and the density distribution remains a key subject for future original research and reviews.

The remainder of this paper is organised as follows. In Section 2, we provide an introduction into the origins of density and some ancillary estimates that help with the interpretation of density effects. In Section 3, we lay out how the evidence base was collected and classified. Section 4 summarises the evidence by outcomes and attributes. Section 5 presents a discussion of our original density elasticity estimates. Section 6 condenses the evidence (including our original estimates) to 15 outcome-specific density elasticity estimates. Section 7 discusses the monetary equivalents of an increase in density. The final Section 8 concludes. We also provide an extensive technical Supplementary material 1 with additional results and explanations, which is essential reading for those wishing to use our quantitative results in further research (recommended elasticities and monetary equivalents).

2. Background

In this section, we provide some theoretical background and ancillary empirical analyses that will guide the interpretation of the evidence base.

2.1. Origins of density

The first columns of Table 1 summarise the distribution of population density by OECD functional urban areas (FUA), comparing the US to the rest of the world. While, on average, density in US cities is relatively low, the variation, at a coefficient of variation of about one, is similarly striking in both samples. Another notable insight from Table 1 is that the variation in density within US FUAs is about two and a half times the variation across FUAs.

Economic theory offers a range of explanations for this large variation in density. In a world without internal or external scale economies, density naturally results from the fundamental productivity and amenity value of a location. Exogenous geographic features such as fertile soil, moderate climate, or access to navigable rivers attract economic activity, leading to growing cities. Classic urban economics models predict that larger cities will be denser since positive within-city transport costs limit horizontal urban expansion (Brueckner, 1987). Urban growth, therefore, drives up the average rent in a city, leading to lower use of space and a substitution effect on the consumption side. Since building taller becomes profitable, higher rents lead to densification due to a more intense use of land and a substitution effect on the supply side. Within cities, densities are higher close to desirable locations (such as the CBD) where rents are particularly high to offset for transport cost. Transport innovations (e.g. mass-produced cars) allow for horizontal expansion and, ceteris paribus, reduce urban density.

Reflecting the shift towards knowledge-based urban economies (Michaels et al., 2013), recent models feature agglomeration externalities (Lucas and Rossi-Hansberg, 2002; Ahlfeldt et al., 2015) making density a cause and an effect of productivity and utility. This class of models features multiple equilibria so that cities may be dense and monocentric or polycentric and dispersed. Yet, due to agglomeration-induced path dependency, contemporary economic geography often follows features that were important in the past, e.g. agricultural land suitability (Henderson et al., 2018) or portage sites (Bleakley and Lin, 2012). Similarly, the compact monocentric city structure that is characteristic for historic cities has been argued to be more resilient to shocks (e.g. natural disasters, or transport innovations) in cities that were already large about a century ago, the time when external returns and mass-produced cars presumably started to become increasingly important (Ahlfeldt and Wendland, 2013).

In practice, and at the heart of the policy dimension of this paper, density is also determined by various land use regulations, such as urban growth boundaries, preservation policies, as well as height, floor area ratio, and lot size regulations, which often have their origins in history (McMillen and McDonald, 2002; Siodla 2015). For a comprehensive review of the role of history in urban economics research, see Hanlon and Heblich (2018).

Given the endogeneity of density, separating the effects of density on an economic outcome from the effects of location fundamentals represents an identification challenge. Natural experiments such as the division of a city due to exogenous political reasons (Ahlfeldt et al., 2015) are rare. Plausible instruments for density are often difficult to find, although some researchers have exploited geology as a factor that likely impacts on the distribution of economic activity, but not on an economic outcome of interest (Combes et al., 2010). Our reading is that, for the most part, the literature implicitly exploits the idea that much of the spatial variation in density is rooted in history. Many of the results summarised below are informative to the extent that density is determined by factors that were relevant in the past and have a limited direct effect on economic outcomes today.

2.2. Density and city size

The relationship between city size and density is critical to the interpretation of our evidence base. Given the theoretical link discussed above, it is perhaps not surprising that the literature refers to actual density, the population normalised by the geographic size of a city, and city size, the total population, interchangeably.

Some researchers have attempted to disentangle the effects of density and city size (Cheshire and Magrini, 2009). At the heart of such a separation is the idea that different types of agglomeration economies operate at different spatial resolutions (Rosenthal and Strange, 2001). Separating the effects of city size and density corresponds to separating the effects of different agglomeration economies (and diseconomies), some of which operate over large distances (such that city size matters), while others are more localised (such that density matters). While separating the effects of density and city size is interesting, it is also challenging because the geographic size of an integrated urban area cannot grow infinitely, which implies that density and city size cannot vary independently.

Our reading of the literature is that in most studies identifying density effects from between-city (as opposed to within-city) comparisons, city population implicitly changes as city density changes (and vice versa). The evidence from between-city comparisons reviewed here should be interpreted in that light, since compact-city policies aiming at changing density while keeping population constant may result in smaller effects, if there is a genuine city-size effect that is independent from density. As an example, if productivity gains from labour market pooling operated at the city scale over relatively large commuting distances without spatial decay, increasing density while holding population constant would not increase productivity. Reassuringly, the estimates from between-city and within-city studies (which hold population constant) tend to be quite similar conditional on us making the following adjustment.

To translate estimated city size elasticities from the literature into density elasticity estimates, we use an estimate of the elasticity of (population) density with respect to city size (population) derived from a multi-country FUA-level data set (OECD, 2016) and the following empirical specification:

$$\ln\left(A_{i,c}\right) = a\ln\left(P_i\right) + \mu_c + \varepsilon_{i,c}, \tag{1}$$

where $A_{i,\,c}$ is the geographic area of FUA i in country c, P_i is the land area of the FUA, and μ_c is a country fixed effect. The city size elasticity of density is implicitly determined as $d\ln(P_i/A_i)/d\ln(P_i) = \alpha = 1 - a$. Compared to using the log of density as dependent variable, this estimation strategy avoids the mechanical endogeneity problem that arises if population shows up on both sides of the equation. Our preferred estimate of a is 0.57, which implies a city size elasticity of density of $\alpha = 0.43$. Therefore, we expect density elasticity estimates to be slightly more than twice as large as population elasticity estimates if the underlying economic mechanisms are the same. We note that our estimate of a is broadly consistent with the 0.7 estimate for French cities by Combes et al. (2018). Details related to the estimation of Eq. (1), the estimation results, and the various transformations used to standardise the results reported in the literature are reported in Section 2 of Supplementary material 1.

2.3. Density and the supply side

As discussed above, the positive city size elasticity of density results from an interplay of the demand side and the supply side of the urban economy. Higher rents in larger cities lead to higher densities. Higher densities, in turn, imply that it is more expensive to provide space, pushing rents up. Larger cities are therefore theoretically expected to be denser and have higher rents, with the latter being the cause and effect of higher construction costs. The empirical evidence is generally in line with these expectations. Helsley and Strange (2008) provide anecdotal evidence of larger cities having taller buildings. Gyourko and Saiz (2006) show that constructing a standard home is more expensive in denser areas, even after controlling for differences in geography (high hills and mountains), regulatory regimes (housing permits, regulatory chatter), and labour market conditions (e.g. wages, unionisation). According to Ellis (2004), midrise stacked flats are twice as expensive to construct as single-family detached housing. Ahlfeldt and McMillen (2018) estimate a height elasticity of construction cost of 0.25 for small structures (five stories and below), and even higher elasticities for taller structures. However, estimates of the effect of density on construction cost that capture the changes in the composition of building types (a structure effect) as well as changes in the cost of building equivalent units (a location effect) to our knowledge do not exist to date.

To substantiate the interpretation of our evidence base, we therefore provide novel estimates of the density elasticity of (per-unit) construction costs. We combine a micro-data set on building constructions from Emporis with census tract level population and area data from the 2010 US Census and the American Community Survey (ACS). In an alternative approach, we create a construction cost index using structure-type-specific construction cost estimates from Ellis (2004) and information on the structure-type composition from the ACS (Ruggles et al., 2017). This index exclusively captures variation in construction costs due to the composition of structure types (the structure effect). The estimated density elasticity of this index can be combined with the estimated density elasticity of the cost of a standard home (the location effect) from Gyourko and Saiz (2006) to give an estimate of the gross density effect.

From the results of both analyses, we conclude that 0.04–0.07 represent a conservative range for the density elasticity of construction cost in the US. This estimate is a gross estimate that includes all structure effects and location effects that are associated with density (including differences in regulation, geology and labour market conditions that may be cause or effects of density). A detailed discussion of the effects of density on construction cost is in Supplementary material 1. We will return to this parameter when reviewing the evidence on the effects of density on rents, wages and amenities.

3. The evidence base

3.1. Collection

In line with standard best-practice approaches of meta-analytic research, as reviewed by Stanley (2001), our literature search is carried out in several stages.[5] We do not impose any geographical restrictions (with respect to the study area) and consider various geographic layers (from micro-geographic scale to cross-region comparisons).

First, we conduct 260 separate searches for various combinations of category-specific keywords (combinations of outcomes and empirically

[5] Recent examples of classic meta-analyses in economics include studies by Eckel and Füllbrunn (2015), Melo et al. (2009), and Nitsch (2005).

observed variables) in academic databases (EconLit, Web of Science, and Google Scholar) and specialist research institute working paper series (NBER, CEPR, CESIfo, and IZA). Second, we expand on relevant research strands by conducting an analysis of citation trees. Third, we ask colleges in our research networks to recommend relevant research (by personal mail and a call circulated in social media) and add studies that were previously known to us or came up in discretionary searches.[6] We keep track of the stage at which the evidence is added to control for a bias due to a potentially selective research network. To prevent publication bias, we explicitly consider studies that were published as edited book chapters, PhD theses, reports, in refereed journals or in academic working paper series (we were also open to other types of publications). This process, which is described in more detail in Supplementary material 1 to this paper and in Ahlfeldt and Pietrostefani (2017), results in 268 relevant studies, which include 473 conceptually distinct analyses. We typically keep multiple estimates (analyses) from the same study if they refer to different dependent variables or geographic areas.

A restriction to elasticity estimates that are explicitly reported in publications shrinks the sample by about 50% to 242 analyses in 127 studies. We make some effort, however, to increase the evidence base. We infer density elasticity estimates from reported city size elasticity estimates using the estimated elasticity of city size with respect to density discussed above. Similarly, we conduct back-of-the-envelope calculations to approximate density elasticity estimates if results are reported as estimated marginal effects in levels, semi-elasticities, or in graphical illustrations. We also make some adjustments to allow for a consistent interpretation within categories. As an example, we convert estimates of the density elasticity of land price into estimates of the density elasticity of housing rent assuming a Cobb-Douglas housing production function (Epple et al., 2010) and a land share of 0.25 (Combes et al., 2018; Ahlfeldt et al., 2015). Finally, some authors kindly provided density elasticity estimates on request, which were not reported in their papers (e.g. Couture, 2016; Tang, 2015; Albouy, 2008). This way, we increase the quantitative evidence base by more than 100 estimates to 347 analyses in 180 studies. The final quantitative sample is comparable to the full sample (473 analyses from 268 studies) across a range of characteristics that we introduce in the next subsections (see Supplementary material 1 Section 2).

A more complete discussion of the various adjustments made to ensure comparability of the evidence is in Supplementary material 1 Section 2. A complete list of studies along with the encoded attributes introduced in the following sections is provided in Supplementary material 1.

3.2. Attributes

We choose a quantitative approach to synthesise our broad and diverse evidence base. As with most quantitative literature reviews we use statistical approaches to test whether existing empirical findings vary systematically in the selected attributes of the studies, such as the geographic context, the data or the methods used. Therefore, we encode the results and the various attributes of the reviewed studies into variables that can be analysed using statistical methods.

The typical approach in meta-analytic research is to analyse the findings in a very specific literature strand. The results that are subjected to a meta-analysis are often parameters that have been estimated in relatively similar econometric analyses. In such instances, it is useful to collect specific information concerning the econometric setup. In contrast, the scope of our analysis is much broader. Our aim is to synthesise the evidence on the economic effects of density across a range of outcome categories. We consider studies from separate literature strands that naturally use very different empirical approaches. The information we collect is, therefore, somewhat more generic and includes the following attributes:

i) The outcome category, one for the 15 categories (see Table A1 for details, Supplementary material 1 Section 1)
ii) The dependent variable, e.g. wages, land value, crime rate
iii) The study area, including the continent and the country
iv) The publication venue, e.g. academic journal, working paper, book chapter, report
v) The disciplinary background, e.g. economics, regional sciences, planning, etc.
vi) The stage (1–3) at which an analysis is added to the evidence base (see Table A2)
vii) The period of analysis
viii) The spatial scale of the analysis, i.e. within-city vs. between-city
ix) The methodological approach as defined by the Scientific Maryland Scale (SMS) used by the What Works Centre for Local Economic Growth (2016)
The variable can take the following values:
    1. Exploratory analyses (e.g. charts). This score is not part of the original SMS
    2. Unconditional correlations and OLS with limited controls
    3. Cross-sectional analysis with comprehensive controls
    4. Good use of spatiotemporal variation controlling for period and individual effects, e.g. difference-in-differences or panel methods
    5. Exploiting plausibly exogenous variation, e.g. by use of instrumental variables, discontinuity designs or natural experiments
    6. Reserved to randomised control trials (not in the evidence base)
x) The cumulated number of citations, adjusted for the years since publication, which we generate using yearly citations counts per study from Scopus. For non-journal publications, we impute the citation index using data from Google Scholar. Expectedly, our study-based index is closely correlated with journal quality as measured by the SNIP (Source Normalised Impact per Paper) score (Scopus, 2016) and the SCImago Journal Rank (Scimago, 2017). A detailed discussion is in Supplementary material 1.

It is worth pointing out that, in the present context, a higher SMS score does not necessarily imply a higher quality of the evidence. While exploiting plausibly exogenous variation (SMS 4) is certainly desirable to separate the effects of density from unobserved location fundamentals, it is less clear that having a greater set of covariates (SMS 2) improves the analysis if the controls are potentially endogenous. One example frequently found in the literature that gives cause for concerns is the inclusion of multiple variables that capture different shades of urban compactness such as population density, building density and job centrality. Similarly, the inclusion of spatial fixed effects (SMS 3) does not improve the identification if the fraction of the variation in density that is most likely exogenous is cross-sectional, because it is determined by history (see discussion in Section 2.1). Given these ambiguities, our preferred measure for weighting the elasticities in the evidence base is the citation index, which captures the impact an analysis has had within the research community.

In Table 2 we tabulate the distribution of analyses included in this review by selected attributes (as discussed above, one study can include several analyses). While our evidence base to some extent covers most world regions, including the global south, there is a strong concentration of studies from high-income countries and, in particular, from North America. The clear majority of studies have been published in academic journals. The evidence base is diverse with respect to disciplinary background, with economics as the most frequent discipline, accounting for a share of about 30%.

[6] At this stage, we were pointed to a literature on urban scaling in which city size is related to a variety of outcomes. This literature is not part of this review, because unlike with the bulk of the evidence base, the analysis is purely descriptive and not concerned with density (Bettencourt & Lobo 2016; Batty 2008; Bettencourt 2013).

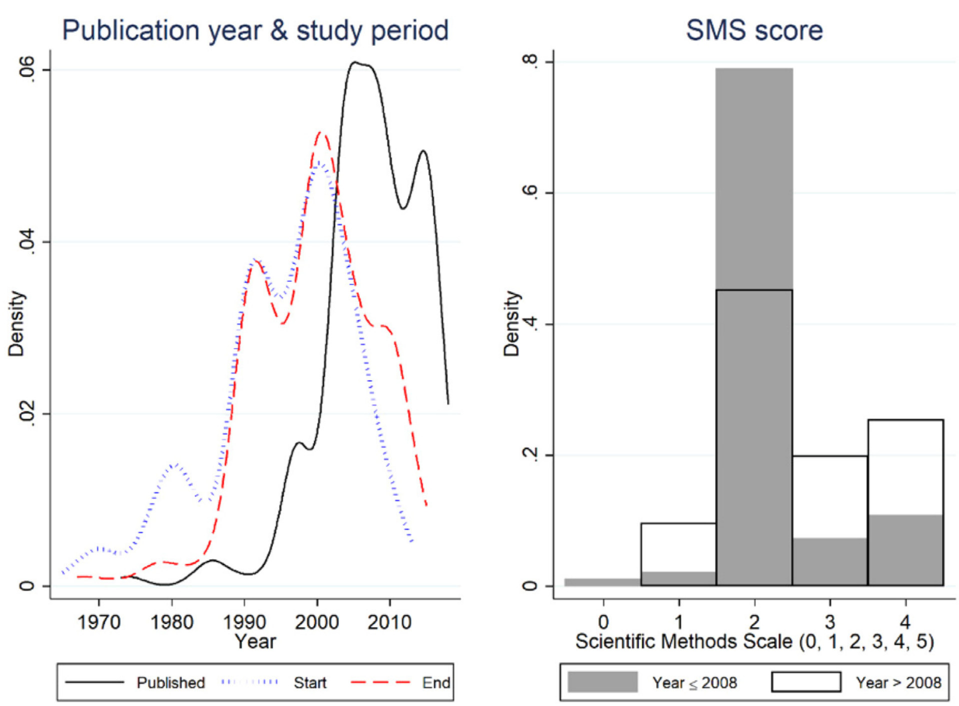

Fig. 1. Distribution of study period and quality of evidence.
Kernel in the left panel is Gaussian. 2008 is the median year of publication. Scientific Methods Scale (SMS) defined above (higher values indicate more rigorous methods).

Table 2
Distribution of analyses by attributes I.

World region		Publication		Discipline	
North America	208	Academic Journal	266	Economics	100
Europe	86	Working Paper	62	Transport	72
Asia	34	Report	14	Planning	48
South America	7	PhD	4	Urban Studies	42
World	4	Book chapter	1	Other	34
OECD	3	–	–	Regional Studies	24
non-OECD	3	–	–	Health	14
Oceania	1	–	–	Economic Geography	9
Africa	1	–	–	Energy	4

Notes: Assignment to disciplines based on publication venues. Studies contain multiple analyses if density effects refer to multiple outcomes.

In Fig. 1, we illustrate the distribution of publication years, the study period, and the type of methods used, according to the SMS. The evidence, overall, is very recent, with the great majority of studies having been published within the last 15 years, reflecting the growing academic interest in the topic. Most studies use data from the 1980s onwards. A clear majority of studies score two or more on the SMS, which means there is usually at least some attempt to disentangle density effects from other effects, often including unobserved fixed effects and period effects. Distinguishing between studies published before or after the median year of publication (2008) reveals a progression towards more rigorous methods that score three or four on the SMS.

4. Density elasticity estimates in the literature

4.1. Results by outcome category

In Table 3 we summarise the quantitative results in our evidence base. We made an effort to condense the elasticity estimates into a limited number of outcome groups. Because of the great variety of outcomes in the evidence base we frequently report more than one elasticity per outcome category to which we will refer to in the remainder of the paper (indicated by ID). Throughout this paper, all outcomes are expressed such that positive values imply economic effects that are typically considered to be positive in a normative sense in the relevant literatures.

Given the variety of outcomes we do not discuss each result here but leave it to the interested reader to pick their finding of relevance. We note, however, that there is significant variation in the quantity of the evidence base (N) and the quality of the underlying evidence (as well as other attributes) and we urge these differences to be taken into account when considering the evidence. Caution is warranted, not only when the evidence base is quantitatively small (small N), but also when it is inconsistent. A useful indicator is a standard deviation (SD) that is large compared to the mean, like, for example, pollution reduction. We also note that the results summarized in Table 3 cannot generally be interpreted as causal estimates since the estimated density effects, in many cases, may capture the effects of correlated location fundamentals. For a selected set of outcome groups (one per category) we provide a critical discussion of the quantity and the quality of the evidence in Section 4 of Supplementary material 1. We report the mean elasticity weighted by our citation index in Table 3. The interested reader will find results using alternative weighting schemes in Section 2 of Supplementary material 1.

4.2. Results by attributes

For a pooled analysis of the sources of heterogeneity in the evidence base, we normalise category-specific elasticity estimates so that they have a zero mean and a unit standard deviation within the outcome groups listed in Table 3. Fig. 2 reveals that density elasticity estimates tend to decline in the year of publication, the citation index, and the SMS score. This pattern is in line with the increasing popularity of more rigorous methods displayed in Fig. 1.

In Fig. 3, we illustrate how the distribution of normalised elasticity estimates varies in selected attributes. At the bottom of each panel we report (two-sided) Kolmogorov-Smirnov test statistics and significance levels. We find a statistically significant difference in the distributions with respect to publication venue (less positive elasticities in journals) and citation index (less positive elasticities for higher index values), which may reflect publication bias or quality of peer review. Estimated elasticities form higher-density contexts are larger, on average.

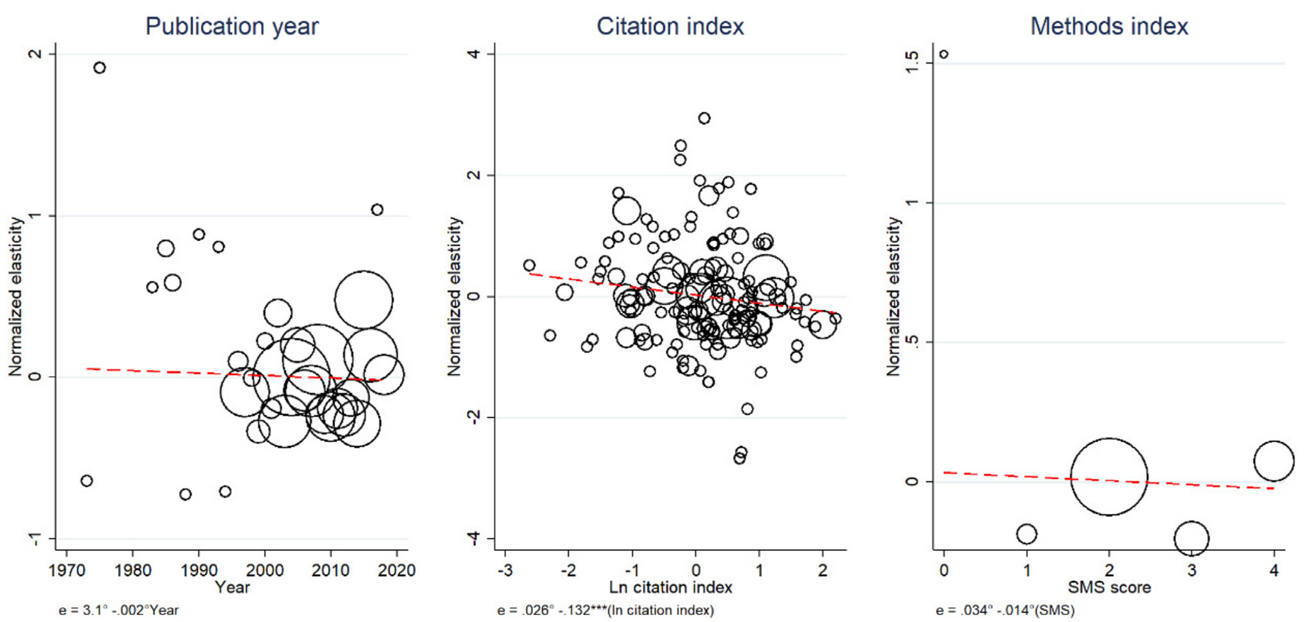

Fig. 2. Normalised elasticity estimates vs. publication year and quality of evidence.
Elasticity estimates (e) are normalised within outcome elasticity groups (listed in Table 3) to have a mean of zero and a standard deviation of one. Citation index defined in Section 2.2. Marker size proportionate to number of observations. Linear fits (dashed lines, parametric results at the bottom) are frequency weighted by observations. °/*/**/*** indicates insignificant/significant at the 10%/5%/1% level (robust standard errors).

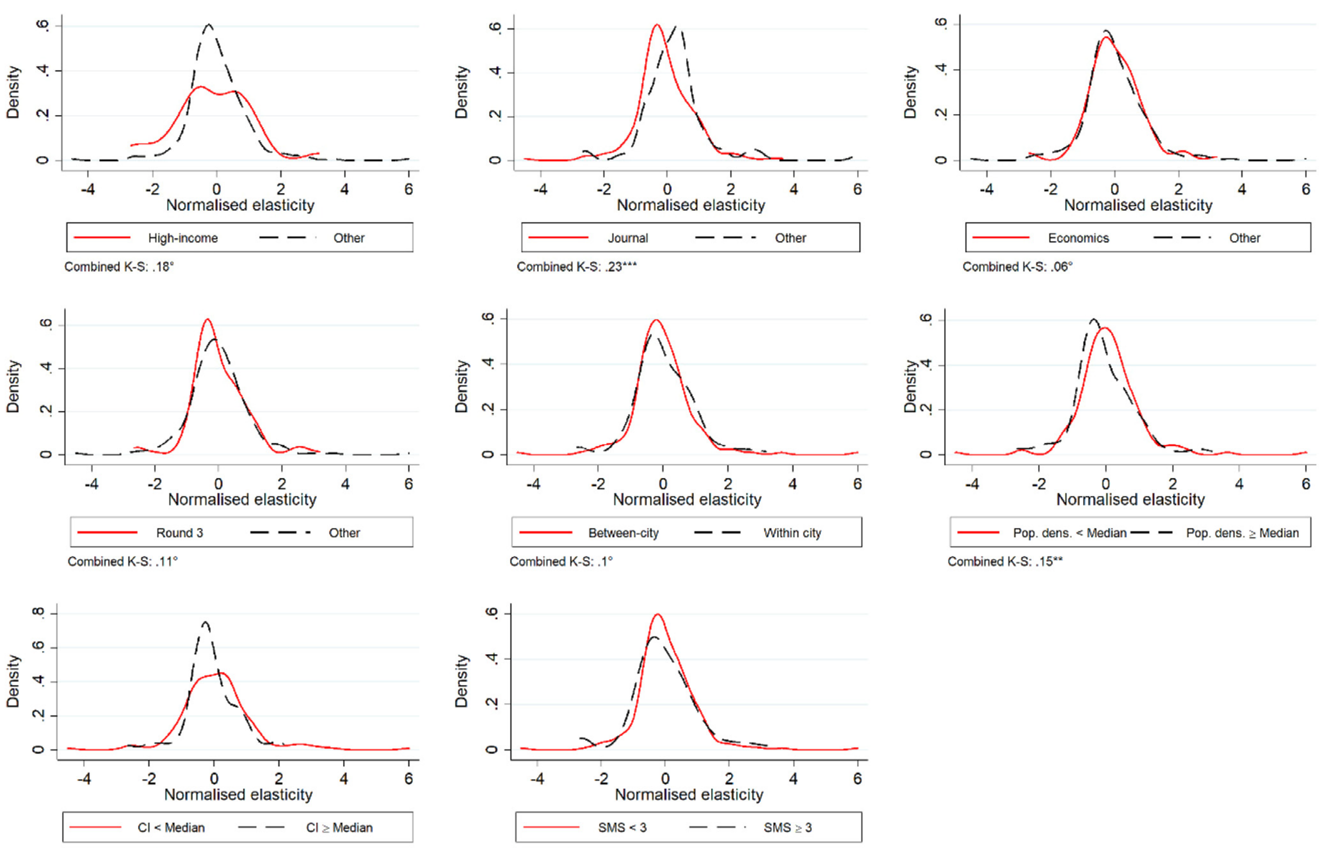

Fig. 3. Distribution of normalised elasticity estimates by attributes.
Elasticity estimates normalised within outcome elasticity groups (listed in Table 3) to have a mean of zero and a standard deviation of one. Non-high-income include low-income and median-income countries according to the World Bank definition. The citation index (CI) defined in Section 2.2. °/*/**/*** indicates insignificant/significant at the 10%/5%/1% level based on a two-sample Kolmogorov-Smirnov test for equality of distribution functions.

Table 3
Density elasticity estimates in the literature.

	Elasticity of outcome		Proportion				Med.	Mean	Elasticity[g]	
ID	with respect to density	N	Poor[a]	Ac.[b]	Econ.[c]	With.[d]	Year[e]	SMS[f]	Mean	S.D.
1	Labour productivity	47	0.19	0.79	0.74	0.06	2007	3.02	0.04	0.04
1	Total factor productivity	15	0.13	0.87	0.80	0.20	2004	2.80	0.06	0.03
2	Patents p.c.	7	0.00	1.00	0.14	0.00	2006	2.86	0.21	0.11
3	Rent	13	0.00	0.69	0.62	0.62	2013	3.00	0.15	0.13
4	Commuting reduction	36	0.03	0.56	0.08	0.56	2005	2.17	0.06	0.12
4	Non-work trip reduction	7	0.00	0.71	0.00	0.86	2005	2.00	−0.20	0.44
5	Metro rail density	3	0.00	1.00	0.00	1.00	2010	3.33	0.01	0.02
5	Quality of life	8	0.38	0.88	1.00	0.13	2014	3.00	0.03	0.07
5	Variety (consumption amenities)	1	0.00	1.00	0.00	0.00	2015	4.00	0.19	–
5	Variety price reduction	2	0.00	0.00	1.00	1.00	2016	4.00	0.12	0.06
6	Public spending reduction	20	0.00	1.00	0.05	0.00	2007	2.00	0.17	0.25
7	90th-10th pct. wage gap reduction	1	0.00	1.00	0.00	0.00	2004	4.00	0.17	–
7	Black-white wage gap reduction	1	0.00	0.00	1.00	0.00	2013	2.00	0.00	–
7	Diss. index reduction	3	0.00	1.00	0.33	0.00	2009	3.33	0.66	0.94
7	Gini coef. reduction	1	0.00	1.00	0.00	0.00	2010	4.00	4.56	–
7	High-low skill wage gap reduction	3	0.00	0.67	1.00	0.00	2013	4.00	−0.13	0.07
8	Crime rate reduction	13	0.00	0.69	0.15	0.92	2014	2.54	0.24	0.47
9	foliage projection cover	1	0.00	1.00	0.00	1.00	2015	1.00	−0.06	–
10	Noise reduction	1	0.00	1.00	0.00	0.00	2012	1.00	0.04	–
10	Pollution reduction	18	0.44	0.33	0.33	0.39	2014	2.83	0.04	0.47
11	Energy reduction: Domestic & driving	21	0.10	0.90	0.38	0.24	2010	1.81	0.07	0.10
11	Energy reduction: Public transit	1	0.00	1.00	1.00	0.00	2010	1.00	−0.37	–
12	Speed	2	0.00	0.00	1.00	0.00	2016	4.00	−0.12	0.01
13	Car usage (incl. shared) reduction	22	0.00	0.95	0.00	0.95	2004	2.00	0.05	0.07
13	Non-car use	76	0.05	0.79	0.00	0.86	2006	2.03	0.16	0.24
14	Cancer & other disease reduction	5	0.00	1.00	0.00	0.60	2000	2.40	−0.33	0.20
14	KSI & casualty reduction	4	0.00	1.00	0.00	0.00	2003	2.00	0.01	0.61
14	Mental-health	1	0.00	1.00	0.00	1.00	2015	2.00	0.01	–
14	Mortality reduction	3	0.00	1.00	0.00	0.00	2010	2.00	−0.36	0.17
15	Reported health	3	0.00	1.00	0.00	0.00	2013	1.00	−0.27	0.11
15	Reported safety	1	0.00	1.00	0.00	1.00	2015	2.00	0.07	–
15	Reported social interaction	6	0.00	0.17	0.83	0.00	2007	3.50	−0.13	0.19
15	Reported wellbeing	1	0.00	1.00	1.00	0.00	2016	3.00	0.00	–
	Sum	347								

Notes:.
[a] Poor countries include low-income and median-income countries according to the World Bank definition.
[b] Published in academic journal.
[c] Belongs to the economics discipline.
[d] Exploits within-city variation.
[e] Year of publication.
[f] Scientific Methods Scale (SMS) defined in Section 3.2 (higher values indicate more robust methods).
[g] Weighted by the citation index introduced in Section 3.2 and Supplementary material 1 Section 1.2. Outcome categories correspond to ID as follows: 1: Productivity; 2: Innovation: 3: Value of space; 4: Job accessibility; 5: Services access; 6: Efficiency of public services delivery; 7: Social equity; 8: Safety; 9: Open space preservation and biodiversity; 10: Pollution reduction; 11: Energy efficiency; 12: Traffic flow: 13: Sustainable mode choice; 14: Health; 15: Well-being.

Table 4 presents the results of a multivariate analysis simultaneously controlling for all attributes considered in Fig. 3. We first run a pooled regression using the normalised estimated density elasticity as an outcome. Being published in an academic journal decreases the estimated elasticity by a 0.4 standard deviation. In addition, a one standard-deviation increase in the citation index results in a 0.09 standard deviation reduction in the estimated elasticity. The conditional effect of a high SMS score is insignificant, but the point estimate is negative. So, in line with Figs. 2 and 3, the overall impression is that higher quality is associated with less positive density elasticity estimates.

In the remaining columns of Table 4, we perform meta-analyses (Stanley and Jarrell, 1989; Melo et al., 2009) of the raw elasticity estimates in some of the more populated outcome categories. The first interesting finding is that once we control for study fixed effects, we find that the estimated density elasticity of wages in non-high-income countries is about twice as large as for high-income countries (column 3). It is worth noting that this effect is identified from one multi-country study covering Brazil, China, and India, in addition to the US (Chauvin et al., 2016), which is why we do not add further controls to save degrees of freedom. However, the unconditional citation-weighted mean in the evidence base is 0.08 for non-high-income countries (from 9 analyses), confirming the 100% premium over high-income countries (see Table A11b in Supplementary material 1 for a tabulation of mean elasticity estimates by high-income and non-high-income countries).

The important second insight is that if the population density in the studied area increases by 1000 inhabitants per square kilometre, the estimated density elasticity of rent increases by 0.063, on average. This effect is qualitatively and quantitatively consistent with recent evidence from French cities. Combes et al. (2018) show that the estimated elasticity can vary from 0.205 for a small urban area to 0.378 for an urban area of the size of Paris. Applying the 0.063-estimate from Table 4, column (4), this corresponds to an increase in density by 2750 inhabitants per square kilometre, which in turn corresponds to going from cities like Grenoble or Lens (1000/km^2) to a city like Paris (3700/km^2) (Demographia, 2018). In line with Glaeser and Gottlieb (2008), we do not find a similar effect of density on the estimated density elasticity of wages. So it appears that increasing cost of density rather than decreasing productivity gains curb agglomeration benefits, leading to a bell-shaped net-agglomeration benefits curve (Henderson, 1974).

The third relevant finding is that the density elasticity estimates of sustainable mode choice are significantly lower for non-high-income

Table 4
Meta-analysis of density elasticity estimates.

Category ID	(1) Normalised density elasticity estimate All	(2) Estimated density elasticity of wages 1	(3) Estimated density elasticity of wages 1	(4) Estimated density elasticity of rent 3	(5) Estimated density elasticity of commuting reduction 4	(6) Estimated density elasticity of energy use reduction 11	(7) Estimated density elasticity of sustainable mode choice 13
Non-high-income country	−0.111	0.025	0.050***	–	−0.247	−0.195	−0.162***
	(0.25)	(0.02)	(0.00)		(0.21)	(0.26)	(0.04)
Not published in academic journal	0.401**	0.004		−0.021	0.150	0.364***	0.164
	(0.19)	(0.02)		(0.07)	(0.13)	(0.10)	(0.16)
Non-economics discipline	0.043	0.007		−0.081	0.041	0.003	–
	(0.18)	(0.02)		(0.07)	(0.07)	(0.06)	
Round 3[a]	0.077	0.022*		−0.109+	0.003	0.101*	−0.178**
	(0.18)	(0.01)		(0.06)	(0.06)	(0.05)	(0.07)
Within-city variation	−0.136	−0.020+		−0.146	−0.071	0.187**	−0.085
	(0.18)	(0.01)		(0.10)	(0.07)	(0.07)	(0.11)
Citation index normalised by s.d.	−0.091*	−0.005+		0.307+	0.058	−0.010	0.030
	(0.05)	(0.00)		(0.18)	(0.05)	(0.01)	(0.04)
SMS >=3	−0.203	−0.014		−0.040	−0.025	0.070	−0.007
	(0.16)	(0.01)		(0.08)	(0.05)	(0.07)	(0.09)
Pop. density in study area (1000/km^2)	−0.008	−0.005		0.063**	0.011	0.017	−0.001
	(0.01)	(0.00)		(0.03)	(0.07)	(0.04)	(0.00)
Constant	0.000	0.048***	0.048***	0.131***	0.051**	0.115***	0.183***
	(0.05)	(0.01)	(0.00)	(0.02)	(0.02)	(0.02)	(0.04)
Study effects	–	–	Yes	–	–	–	–
N	337	47	47	13	36	21	76
r2	0.043	0.126	0.846	0.805	0.306	0.763	0.131

Note: Normalised elasticity estimates in (1) are normalised within outcome groups (those listed in Table 3) to have a zero mean and a unity standard deviation. Citation index normalised by the global standard deviation. All explanatory variables are normalised to have a zero mean within outcome groups. 10 observations drop out in (1) due to normalisation within categories with singular observations. Non-high-income countries include low-income and median-income countries according to the World Bank definition. Population density in study area is from Demographia World Urban Areas (2018).

[a] Round 3 consists of previously known evidence and recommendations by colleagues. Standard errors (in parentheses) are clustered on studies (one study can contain multiple analyses, the unit of observation).

+ $p < 0.15$.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

countries. A potential explanation that is consistent with the large estimated density elasticity of wages in developing countries is an indirect income effect that works in the opposite direction of the direct density effect. While a compact urban form ceteris paribus may favour alternative modes, higher incomes in more urbanised areas increase the affordability of car trips. Fourth, the mean estimated density elasticity of energy consumption reduction is much larger when identified from studies exploring *within-city variation.* In this context, it is worth noting that the citation-weighted unconditional mean density elasticity of energy consumption reduction, at 0.16, is much larger for non-high-income countries than for high-income countries. Given the small numbers (two estimates from non-high-income countries), it is difficult to separate the *within-city* and *non-high-income country* effects. It may be that within cities, population density is generally more strongly correlated with the share of multi-family houses, which tend to be more energy efficient. This relationship might be particularly strong in developing countries where often high densities imply formal housing as opposed to informal housing (Henderson et al., 2016).

5. Original density elasticity estimates

While the evidence base on the quantitative effects of density summarised above is rich and reasonably consistent for outcomes like productivity or mode choice, it is thinner and less consistent for many other outcomes. To enrich the evidence base in some of the less-developed categories, we contribute some transparent elasticity estimates using data from the OECD functional urban area and regional statistics database and the following regression model:

$$\ln\left(Y_{i,c}\right) = \beta \ln\left(\frac{P_i}{A_i}\right) + \tau \ln\left(\frac{G_i}{P_i}\right) + \mu_c + \epsilon_{i,c}, \qquad (2)$$

where $Y_{i,c}$ is an outcome in city i in country c, P_i, A_i, μ_c are population, geographic area, and country fixed effects as in Eq. (1), and G_i is GDP. The coefficient of interest is β, which gives the estimated density elasticity of an outcome controlling for GDP per capita and unobserved cross-country heterogeneity. Where either population or area forms part of the dependent variable, we instrument population density using the (ln) rank within the national population density distribution as an instrument. Table 5 summarises the key results. Full estimation results, in each case for a greater variety of model specifications, are in Supplementary material 1 (Section 3).

We find a negative association between well-being and density, which seems to be more pronounced across countries than within. Still, the results support the singular comparable result found in the literature (Glaeser et al., 2016). Our results further support the average findings in the evidence base, in that innovation (number of patents) increases in density and crime rates, energy use (carbon emissions), and average road speeds decrease in density.

Conflicting with the mean elasticities in the evidence base reported in Table 3, we find that pollution concentrations are higher in denser cities. At the local level, the effect of concentrating sources of pollution in space dominates the effect of reduced aggregate emissions (due to shorter car trips and more energy-efficient housing). Our estimate has been confirmed by two recent

Table 5
Original elasticity estimates.

	Ln patents p.c.[a]		Ln broadband p.c.[b]		Ln income quintile ratio[b]		Ln Gini coefficient [b]	
Ln dens.	0.349***	0.129*	0.034***	0.01	0.024	0.035**	−0.007	0.025***
FE	–	Yes	–	Yes	–	Yes	–	Yes
IV	–	Yes	–	Yes	–	–	–	–
	Ln poverty rate[b] Ln poverty rate[b]		Ln homicides p.c.[b]		Ln green density[b] (administrative)		Ln urban green density[a] (functional economic)	
Ln dens.	−0.013	0.032	−0.166***	−0.048	−0.267***	−0.245***	0.283**	0.761*
FE	–	Yes	–	Yes	–	Yes	–	Yes
IV	–	Yes	–	Yes	–	Yes	–	Yes
	Ln green p.c.[c]		Ln pollution (PM2.5)[b]		Ln CO2 p.c.[b]		Ln speed[a,d] freeway	arterial
Ln dens.	−0.717***	−0.239	0.220***	0.124***	−0.224***	−0.173***	−0.008	−0.063***
FE	–	Yes	–	Yes	–	Yes	–	–
IV	–	Yes	–	–	–	Yes	–	–
	Ln mortality rate[b]		Ln mortality rate: transport[b]		Ln life expectancy at birth[b]		Ln self-reported well-being[b]	
Ln dens.	−0.046***	−0.017	−0.150***	−0.099***	0.013***	0.007*	−0.023***	−0.007**
FE	–	Yes	–	Yes	–	Yes	–	Yes
IV	–	Yes	–	Yes	–	–	–	–

Notes: Density (dens.) is population density (population / area). All models control for ln GDP p.c. Fixed effects (FE) are by country. IV is rank of a city in the population density distribution within a country.

[a] Data from OECD.Stat functional economic areas.

[b] Data from OECD.Stat administrative boundaries (large regions).

[c] Data from OECD.Stat administrative boundaries (small regions, excluding GDP control due to unavailability of data for the US).

[d] Speed data from Lomax et al. (2010). Poverty line is 60% of the national median income. Speeds are measured during peak time.

* $p < 0.1$.

** $p < 0.05$.

*** $p < 0.01$, with standard errors clustered on FE where applicable.

studies (Carozzi and Roth, 2018; Borck and Schrauth, 2018). Furthermore, our results consistently suggest that income inequality increases in density. Our results are qualitatively and quantitatively (see the results for US cities reported in Section 3.3 in Supplementary material 1) consistent with Baum-Snow et al. (2017). But there is some contrast to the reviewed literature that has found mixed results, with many studies pointing to lower inequalities at higher levels of economic density. To reconcile the evidence, we note that the evidence base contains several case studies on a within-city scale, but our comparison is across economic areas. It seems plausible that the mechanisms affecting equity dimensions are different on a within-city (segregation) and a between-city (skill complementarity) scale, but further research is required to substantiate this intuition. We note that the statistically insignificant effect of density on crime (conditional on country fixed effects), masks heterogeneity across US and non-US cities. In line with Glaeser and Sacerdote (1999), we find that crime rates increase in density for US cities, whereas the opposite is true for other OECD countries (see Supplementary material 1).

Our estimates of the relationship between green coverage and population density are without precedent. The elasticity of green density with respect to population density qualitatively depends on the spatial layer of analysis. At regional level (administrative boundaries) the spatial units cover both urban and rural areas. The negative elasticity estimate likely reflects that an increase in population implies a larger share of urban, at the expense of non-urban land. Functional economic areas are designed to cover exclusively urban areas. The positive elasticity estimate likely reflects that within an urbanised area, increasing population density preserves space for urban parks and suburban forests. Because we focus on the effects of urban form in this paper, the latter is our preferred estimate. We note that the relatively large elasticity estimated conditional on country fixed effects is driven by a suspiciously large elasticity estimated across US cities (>1.4), whereas the within-country elasticity estimate for the rest of the world is in line with the baseline elasticity estimate from the cross-sectional model excluding fixed effects. Therefore, in this case we prefer the conservative non-fixed effects model. The estimated elasticity of per capita green area with respect to population is negative, as expected. Our preferred elasticity estimate (−0.283) is of roughly the same magnitude as the estimated elasticity of green space value with respect to population density of 0.3 (Brander and Koetse, 2011) suggesting that congestion (number of users) and the value of green space increase at roughly the same rate.

6. Recommended elasticity estimates

In Table 6 we condense the quantitative evidence, including our original estimates, into recommended density elasticity estimates which we provide for each outcome category. Specific to each category, we either recommend a citation-weighted mean across the elasticity estimates in our evidence base as reported in Table 3, an estimate from a high-quality original research paper or one of our original estimates. The selected dedicated analyses use comprehensive data and make sensible choices in the research design, i.e. they avoid excessive “overcontrolling” for endogenous variables and exploit plausibly exogenous variation. In general, we prefer the citation-weighted mean in the evidence base as well as estimates from dedicated high-quality original research papers over our original estimates. We also prefer estimates from dedicated high-quality papers over the weighted means in the evidence base if the evidence base is thin or inconsistent, in particular if the recommended elasticity estimate is in line with our original analysis of OECD data.

Our aim is to provide a compact and accessible comparison of density effects across categories. The baseline results are best understood as referring to high-income countries. Where possible, we acknowledge cross-country differences in Table 6. Nevertheless, we wish to remind the reader that we likely miss substantial context-specific heterogeneity. Moreover, the quality and quantity of the evidence base is highly heterogeneous across categories. We strongly advise to consult section 4 in Supplementary material 1, which provides a discussion of the origin of each of the recommended elasticity estimate against the quality and quantity of the evidence base, before applying any of the elasticity estimates reported in Table 6 in further research. In a nutshell, we see

Table 6
Recommended elasticity estimates by category.

ID	Elasticity	Value	Comment
1	Wage	0.04	Citation-weighted mean in review, roughly in line with Melo et al. (2009). 0.08 for non-high-income countries. Net of selection effects, elasticity estimates about halve (Combes and Gobillon 2015).
2	Patent intensity	0.21	Citation-weighed mean in review, in line with original analysis of OECD data.
3	Rent	0.15	Citation-weighed mean in review. In line with evidence from the US (dedicated analysis based on Albouy and Lue, 2015 data). Estimated elasticity increases in density (original meta-analysis) and is 0.21 for France (Combes et al., 2018).
4	Vehicle miles travelled (VMT) reduction	0.06	Citation-weighted mean in review, roughly in line with Duranton and Turner (2018) and Ewing and Cervero (2010).
5	Variety value (price index reduction)	0.12	Dedicated analysis on request using data from Couture (2016), in line with Ahlfeldt et al. (2015).
6	Local public spending	0.17	Citation-weighted mean in review, roughly in line with dedicated high-quality paper (Carruthers and Ulfarsson 2003).
7	Inter-quintile wage gap reduction	−0.035	Original analysis of OECD data[a]. −0.057 for the US. US estimate in line with dedicated high-quality paper (Baum-Snow et al., 2017) (Section 3 in Supplementary material 1).
8	Crime rate reduction	0.085	Dedicated analysis on request (Tang 2015), in line with original analysis of OECD non-US city data. Dedicated high-quality paper (Glaeser and Sacardote) and original analysis suggest a negative value for the US.
9	Green density	0.28	Original analysis of OECD data (evidence base non-existent)
10	Pollution reduction	−0.13	Dedicated high-quality paper (Carozzi and Roth 2018). In line with Borck and Schrauth (2018) and original analysis of OECD data
11	Energy use reduction	0.07	Citation-weighted mean in review
12	Average speed	−0.12	Citation-weighted mean of two (no further evidence) high-quality papers (Duranton and Turner 2018; Couture et al., 2018)
13	Car use reduction	0.05	Citation-weighted mean in review
14	Mortality rate reduction	−0.09	Dedicated paper (Reijneveld et al., 1999)
15	Self-reported well-being	−0.0037	Only direct estimate in literature (Glaeser et al., 2016). In line with original analysis of OECD data

Notes: Density elasticity estimates are best understood as referring to large cities in high-income countries. In general, they represent correlations and not necessarily causal estimates. If our recommended elasticities differ between US and non-US cities, we report the former as the baseline and mention the latter in the comments, because, as shown in Table 1, the density distribution of US cities is not representative.

[a] Original analysis uses the wage gap between 80th and the. 20th percentile. 1: Productivity; 2: Innovation: 3: Value of space; 4: Job accessibility; 5: Services access; 6: Efficiency of public services delivery; 7: Social equity; 8: Safety; 9: Open space preservation and biodiversity; 10: Pollution reduction; 11: Energy efficiency; 12: Traffic flow: 13: Sustainable mode choice; 14: Health; 15: Well-being. See Supplementary material 1 section 4 for a critical discussion of the evidence base by category.

sufficient evidence that seriously engages with separating the effects of density from the effects of correlated unobserved fundamentals to allow for a causal interpretation in the following categories: 1: Wage and productivity; 3: Rent, 4: Vehicle miles travelled; 10: Pollution reduction; 12: Average speed. For the other categories, the estimated elasticities are better interpreted as associations in the data. We stress that significant uncertainty surrounds the effects of density on income inequality, urban green, health, and self-reported well-being. In general, the recommended elasticities are best understood as describing area-based effects that include composition effects.

There is an important additional elasticity estimate that is implicitly determined by the elasticity estimates reported in Table 6. Assuming perfect mobility and competition in all markets, all benefits and costs in urban area offers must be compensated by wages and rents (Rosen, 1979; Roback, 1982). The relative quality of life of a place can be inferred from the relative real wage (income after taxes and housing expenditures) residents are willing to give up to enjoy living there, i.e. $\mathrm{dln}Q = \rho \mathrm{dln}r - \mathrm{T}\mathrm{dln}w$, where $\mathrm{dln}Q$, $\mathrm{dln}r$,and $\mathrm{dln}w$ are differentials in quality of life, rents, and wages (in natural logs), ρ is the housing expenditure share and T is one minus the tax rate. The elasticity of quality of life with respect to density can be expressed as: $\frac{\mathrm{dln}Q}{\mathrm{dln}(P/A)} = \rho\frac{\mathrm{dln}r}{\mathrm{dln}(P/A)} - \mathrm{T}\frac{\mathrm{dln}w}{\mathrm{dln}(P/A)}$.

Applying conventional values of $\rho = 1/3$ and $\mathrm{T} = 0.66$ (Albouy and Lue, 2015) and the elasticity estimates reported in Table 6, the resulting quality-of-life elasticity estimate at 0.04 is close to the citation-weighted mean from the evidence base (0.03). However, we must note that there is considerable variation in the collected quality-of-life elasticity estimates including both negative (Chauvin et al., 2016) and positive effects (Albouy and Lue, 2015).

7. Monetary equivalents

For a quantitative comparison of density effects across categories, we conduct a series of back-of-the-envelope calculations to express the effects that would result from a 1% increase in density as per capita PV dollar effects, assuming an infinite horizon and a conventional 5% discount rate (de Rus, 2010). We summarise the results in Table 7. As most of the parameters used in the back-of-the envelope calculations are context-dependent, the table is designed to allow for straightforward adjustments. The monetary effect in the last column (8) is simply the product over the elasticity (3), the base value (5), the unit value (7), a 1% increase in density and the inverse of the 5% discount rate (e.g. $0.04 \times \$35{,}000 \times 1 \times 1\%/5\%$ for the wage effect). By changing any of the factors a context-specific monetary equivalent can be calculated.

The exercise summarised in Table 7 is ambitious and there are some limitations. First, the monetary equivalents are estimates that most closely refer to large metropolitan areas in high-income countries. In drawing conclusions for a specific institutional context, we strongly advise that the assumptions made in Supplementary material 1 section 5 are evaluated with respect to their applicability. Second, the results in Table 7 do not necessarily correspond to the short-run effect of a policy-induced change in density. As an example, an increase in population holding the developed area constant will increase population density, but not necessarily the green density. However, the green density will be higher than in a counterfactual were the population growth was achieved holding density constant. Third, the effects implied by the elasticities apply to marginal changes only, i.e. they should not be used to evaluate the likely effects of extreme changes (e.g. a 100% increase in density) in particular settings. Fourth, while for the not genuinely

Table 7
Present value[a] of a 1% increase in density I: Category-specific effects.

(1) Category ID	(2) Outcome	(3) Elast.	(4) Quantity, p.c., year Variable	(5) Value	(6) Unit value Unit	(7) Value	(8) PV of 1% dens. incr. Incr.inc.inc. ($)
1	Wage	0.04	Income ($)	35,000	–	1	280
2	Patent intensity	0.21	Patents (#)	2.06E-04	Patent value ($/#)	793K	7
3	Rent	0.15	Income ($)	35,000	Expenditure share	0.33	347
4	VMT[b] reduction	0.06	VMT[b] (mile)	10,658	Priv. cost $/mile	0.83	107
5	Variety value[c]	0.12[b]	Income ($)	35,000	Expenditure share[d]	0.14	115
6	Local public spending	0.17	Total spending ($)	1463	–	1	50
7	Wage gap[e] reduction	−0.035	Income ($)	35,000	Inequality premium	0.048	−12
8	Crime rate[f] reduction	0.085	Crimes (#)	0.29	Full cost ($/#)	3224	16
9	Green density	0.28	Green area (p.c., m^2)	540	Park value ($/m^2)	0.3	100
10	Pollution reduction	−0.13	Rent ($)	11,550	Rent-poll. elasticity	0.3	−90
11	Energy use reduction						
	(private and social effects)	0.07	Energy (1 M BTU)	121.85	Cost ($/1 M BTU)	18.7	32
		0.07	CO2 emissions (t)	25	Social cost ($/t)	43	15
12	Average speed	−0.12	Driving time (h)	274	VOT ($/h)	10.75	−71
13	Car use reduction	0.05	VMT[b]	10,658	Social cost ($/mile)[g]	0.016	2
14	Health	−0.09	Mortality risk (#)[i]	5.08E-04	Value of life ($/#)[h]	7M	−64
15	Self-reported well-being[j]	−0.004	Income ($)	35,000	Inc.-happ. elasticity	2	−52

Notes: Monetery equivalents represent area-based effects, including selection effects.
[a] The per-capita present value for an infinite horizon and a 5% discount rate.
[b] Vehicle miles travelled.
[c] Reduction in price index of consumption varieties.
[d] Local non-tradeables: home, entertainment, and apparel and services.
[e] Assuming a wage gap of high-skilled vs. low-skilled that corresponds to the 80th vs. 20th percentiles in the wage distribution.
[f] All crimes against individual and households.
[g] Emissions externality.
[h] Statistical value of life.
[i] Pre-mature (> 70) mortality rate.
[j] Self-reported well-being. See Supplementary material 1 section 5 for a discussion of the assumptions on quantities and unit values by category.

area-based outcomes we would ideally apply density effects that come net of selection effects, the literature only offers such estimates in the productivity category. So, for consistency across categories, we strictly apply the baseline elasticities capturing area-based effects from Table 6. Section 5 in Supplementary material 1 provides a more detailed discussion of the evidence base that should be consulted before there is any further use of the suggested monetary equivalents in Table 7.

Despite these limitations, Table 7 offers novel insights into the direction and the relative importance of density effects. The density effect on wages, which has been thoroughly investigated in the agglomerations literature, is large, but not as large as the effect on rents, on average.[7] Density generates costs in the form of higher congestion and lower average road speeds, which are, however, more than compensated for by the cost reductions due to shorter trips. Agglomeration benefits on the consumption side due to larger and more accessible consumption variety are quantitatively important and amount to more than one-third of agglomeration benefits on the production side (wages). Other quantitatively relevant benefits arising from density include cost savings in the provision of local public services, preserved green spaces, lower crime rates (outside the US), and reduced energy use, which creates a sizeable social benefit (reduced carbon emissions) in addition to private cost savings. Besides the aforementioned congestion effects, the cost of density comes in the form of increased pollution concentration, inequality, adverse health effects and reduced well-being.

[7] The results by Combes at al. (2018) suggest that this result may not apply to small cities as the rent elasticity increases in city size.

Given that we have gone a long way in computing category-specific estimates of costs and benefits that are comparable across categories, a natural question arises: Do the benefits of density exceed the costs and, if so, by how much? To address this question, we conduct a simple accounting exercise in Table 8. We distinguish between private (columns 1–5) and external (column 6) costs and benefits, which residents do not directly experience and likely do not pay for via rents (such as reductions in carbon emissions that have global rather than local effects). To avoid double-counting, we exclude gasoline costs in computing the benefits of shorter average trips (category 4) as this cost-saving is already accounted for by reduced energy consumption (category 11). Also, we correct consumption benefits (category 5) to reflect the pure gains from variety and not savings due to shorter car trips, which are already itemised in category (4). Since health effects are itemised in 14, we use an estimate of the health cost arising from density-related pollution from Carozzi and Roth (2018) to restrict the pollution effect to an amenity channel. The external effect from sustainable mode choice (13) is already itemised in the external benefit of reduced energy use (11) and is thus not counted separately. In the baseline scenario (*Sum* row), we assume that public services are nationally funded. In an alternative accounting (indicated in the bottom of the table), we assume that public services are locally funded, so that density-induced cost savings fully capitalise into rents (via lower taxes).

The standard urban economics framework builds on the spatial equilibrium assumption, which implies that individuals are fully mobile and competition in all markets is perfect. In this framework, rents reflect the capitalised values of productivity and utility so that the sum over rents and wages (column 1) amounting $627, p.c. can be interpreted as

Table 8
Present value[a] effects of a 1% increase in density II: Accounting.

	Outcome	(1) Factor Incomes	(2) Quality of life	(3) Amenity value	(4) Effect on	(5)	(6) External welfare
ID	Category				Owner	Renter	
1	Wage	280	−190[b]	0	190[c]	190[c]	0
2	Innovation	0	0	0	0	0	6
3	Value of space	347	347	0	0	−347	0
4	Job accessibility	0	0	87[d]	87[d]	87[d]	0
5	Services access	0	0	99[e]	99[e]	99[e]	0
6	Eff. of pub. services delivery	0	0	0	0	0	50
7	Social equity	0	0	0	0	0	−12
8	Safety	0	0	16	16	16	0
9	Urban green	0	0	100	100	100	0
10	Pollution reduction	0	0	−47[f]	−47[f]	−47[f]	0
11	Energy efficiency	0	0	32	32	32	15
12	Traffic flow	0	0	−71	−71	−71	0
13	Car use reduction	0	0	0	0	0	0[g]
14	Health	0	0	−64	−64	−64	0
15	Self-reported well-being	0	0	−52	−52	−52	0
	Sum	627	152	100	291	−56	60
	Excl. subj. well-being	–	–	152	342	−4	60
	Locally financed pubic services	–	106		340	−6	
	Factor incomes and externality	686	–	–	–	–	–
	Locally financed pubic services	637	–	–	–	–	–

Notes.
[a] The present value per capita for an infinite horizon and a 5% discount rate. All values in $.
[b] Amenity equivalent of after-tax wage increase assuming a marginal tax rate of 32% as in Albouy and Lue (2015).
[c] After-tax wage increase as discussed in [b].
[d] Excludes $19.18 of driving energy cost ($0.15/mile gasoline cost) discounted at 5%, which are itemised in 11.
[e] Assumes a 10.2% elasticity to avoid double-counting of road trips already included in 4.
[f] Amenity effect, excludes health effect itemised in 14.
[g] Set to zero to avoid double counting with 11. Numbers reported in the "Locally financed pubic services" row assume that cost savings in local public services are fully passed on to residents via lower taxes.

a welfare gain to which the external welfare effects of $60 in column (6) can be added. The spatial equilibrium framework is also the theoretical fundament for the economic quality-of-life literature mentioned above, which infers place-specific amenity values from compensating differentials. With perfectly elastic demand, an increase in rent that exceeds an increase in disposable income necessarily reflects a positive quality-of-life effect.

If mobility is not perfect and/or there is heterogeneity in the preference for locations, rents will not only reflect demand-side conditions (here, amenities), but also supply-side conditions, because local demand is downward-sloping (Arnott and Stiglitz, 1979). Increases in density – or the policies that enforce increased density – may then also increase rents because the cost of supplying space is higher. By implication, observed rent increases do not necessarily reflect demand-driven capitalization effects exclusively, but potentially to some extent spatial differences in the slope of the supply curve (Hilber and Vermeulen, 2016; Hilber, 2017). Distinguishing these scenarios is notoriously difficult, but it is informative to compare the quality-of-life effect inferred from wages and rents to the aggregate amenity effects across categories. If the accounting was precise and complete and demand was perfectly elastic, we would expect the aggregate amenity effect to equal the quality-of-life effect.

The amenity effect reported in column (3) with an PV of $100 per capita, is substantial, but smaller than the after-tax compensating differential ($156) in column (2), suggesting a role for the supply side (as long as demand is locally downward-sloping). The role of self-reported well-being is controversial as it is regarded either as a proxy for individual utility (Layard et al., 2008) or as a component in the utility function that is traded against the consumption of goods and amenities (Glaeser et al., 2016). Indeed, the amenity effect and the quality-of-life effect are closer if we exclude the well-being effect as a (dis)amenity category. Similarly, the gap shrinks if we treat local public services as fully locally financed, which implies that the savings are passed on to individuals and are capitalised into rents.

To assess the potential relevance of density effects on rents that originate from the supply side, we assume a share of structural value in housing of 75% (Ahlfeldt et al., 2015; Combes et al., 2018) and compute a range for the monetary equivalent of the effect of a 1% density increase on construction cost as 0.04–0.07 (estimated density elasticity of construction cost, see Section 2.3) x $35k (income) x 75% (share of structure value) x 33% (expenditure share on housing) x 1% (change in density) / 5% (discount rate) = $70–120. Thus, density-induced increases in the cost of housing supply are a plausible explanation for the gap between the estimated amenity and quality-of-life effects if demand is locally downward sloping. A complementary channel that strengthens the supply-side argument is a scarcity land rent that results from policies that restrict the amount of usable land to increase density (Gyourko et al., 2008; Mayer and Somerville, 2000). A detailed discussion of the effects of density on construction costs is in Supplementary material 1 section 2.2.

In columns (4) and (5) we change the perspective and ask how a policy-induced marginal increase in the density of a city would affect residents. Because costs and benefits of density capitalise into rents, the individual net-benefit depends on housing tenure. Given the positive amenity affect from column (5), it is immediate that homeowners gain, on average, as they receive an amenity benefit without having to pay a higher rent. If they were moving to another area, they would leave the amenity gain behind, but would benefit from a higher housing value. Renters would be negatively compensated for the amenity gain by higher rents, making the implications more ambiguous (Ahlfeldt and Maennig, 2015). The net benefit to homeowners is positive with a combined amenity and wage effect of $291 or more (if there are tax savings or we abstract from the well-being effect). There is a net cost to renters of up to $56 if we include well-being effects and assume that there are no tax effects due to savings in public services. If we exclude the well-being effect and allow for cost savings in public services to be passed on to renters via lower taxes, the net benefit remains negative, but is close to zero. Of course, the flipside is that there is a positive external benefit to land owners and given the non-linearity in the density effect on rent documented in Section 4.2 the effect on renters may be positive in supply-elastic markets.

Overall, the evidence suggests that density is a net amenity. This does not imply, however, that everybody necessarily benefits from densification policies. Renters may be net losers of densification because of rent effects that exceed amenity benefits. The negative net-effect is consistent with a negative density effect on well-being if individuals are attached to some areas more than others. If one is willing to believe that there are strong forces that prevent renters from moving, a supply constraining effect of density can shift renters to a lower utility level, consistent with a negative effect on well-being (or happiness). This is, however, an ambitious interpretation of the evidence as it is impossible to claim full coverage and perfect measurement of amenity effects. It is important to acknowledge that the difference between the amenity effect (in column 3) and the quality-of-life effect (in column 2) of density could simply be due to measurement error (e.g. missing items column 3). Research into the well-being effects of density differentiated by tenure would be informative, but to our knowledge, has yet to be conducted.

8. Conclusion

We provide the first quantitative evidence review of the effects of density on a broad range of outcomes. Synthesising the reviewed evidence and a range of original estimates, we report recommended density elasticity estimates for 15 distinct outcome categories along with monetised values of density effects for application in research and policy analysis. While there are sizeable benefits and costs associated with increases in density, the former exceed the latter for a typical large city in the developed world.

In general, much work lies ahead of the related research fields to consistently bring the evidence base to the quantity and quality levels of the most developed outcome categories productivity and mode choice. For all other categories, more research is required – even if selected high-quality evidence exists – to substantiate the recommended elasticities. At this stage, significant uncertainty surrounds any quantitative interpretation in the categories urban green, income inequality, health, and well-being.

As research progresses and the quantity of the evidence base increases, evidence reviews and meta-analyses become a more important aspect of knowledge generation. Regrettably, the scope of this review was constrained because it was frequently not possible to translate results into a comparable metric. To increase the scope of future reviews and meta-analyses, we encourage researchers to complement the presentation of their preferred results by density elasticity estimates that are comparable to those collected here. Minimally, complete summary statistics need to be provided to allow for a conversion of reported marginal effects. Another feature that hinders comparisons across studies is the common practice of analysing more than one aspect of urban form at once, i.e. simultaneously using multiple spatial variables such as population density, building density and job centrality. Disentangling the sources of the effects of compact urban form is important. But it is difficult to compare such conditional marginal effects estimated under the ceteris paribus condition across studies if the measures of urban form co-vary in reality because they are simultaneously determined. To facilitate future reviews and meta-analyses we encourage researchers to complement their differentiated analyses with simple models that exclusively consider the most conventional measure of urban form, which is density.

We provide suggestive evidence that the costs and benefits of agglomeration may be larger in developing-country cities. However, because the evidence from non-high-income countries is scarce, it is not possible to property evaluate whether our key result that density is a net-amenity generalises to non-high-income countries. An important challenge that lies ahead of the research community is to generate a deeper understanding of heterogeneity in density effects across contexts and the density distribution itself, a necessary condition for inference on optimal levels of density.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jue.2019.04.006.

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