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Characterizing and measuring urban landscapes for sustainability

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Characterizing and measuring urban landscapes for sustainability

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**Abstract**

Urban areas are key to sustainability, and understanding heterogeneity in urban landscapes is important for linking development patterns to ecological, economic, and social health. Here, we characterize the urban landscape for the purpose of revealing structural variations that affect sustainability. We develop a new language and classification schema for breaking down urban areas into sub-metropolitan land units that, unlike administrative boundaries, are based on objective measures of the built and natural environment and are comparable across and within urban areas. These units capture structural differences that population density does not. The classification schema offers a process-based characterization of urban landscapes—one where ‘urban’ is defined by the human and biophysical interactions mediated by the urban environment and complements existing land classification systems, like those based on land use and land cover. As an example, the schema is applied here to understand transportation behaviors—a particular urban process with wide-ranging implications for urban sustainability. Using GIS, satellite, and census spatial data, we apply the classification schema in 909 US urban areas, systematically clustering development with similar structural attributes linked to transportation behaviors. In this way, an urban area is divided into a collection of smaller landscapes, larger than individual households and smaller than census tracts, that are distinct in how they function. The study shows that characterizing the urban landscape in this way can distinguish between neighborhoods with different travel behaviors. Extensions of the schema can be used to monitor and manage urban systems towards sustainability, targeting spatial planning strategies to the micro-geographies where they would be most relevant.

1. Introduction

Urban areas produce the majority of greenhouse gas emissions from final energy use [1], generate the majority of global economic output [2], and are home to more than half of humanity [3]. Their development patterns have been associated with both habitat conservation [4, 5] and degradation [6, 7], both energy consumption [8] and energy efficiency [9–12], and both increased economic opportunities [13] and increased inequities [14, 15]. Urban areas are becoming the frontline for tackling challenges such as climate change, ecosystem degradation, and human health crises. How urban areas develop is central to whether and how much they hinder or help the transition of

societies towards sustainability, here defined as the long-term well-being of people and the planet [16].

Therefore, there is a growing need amongst both urban scientists and practitioners for greater systematic knowledge about urban development patterns. Currently, the primary basis for characterizing urban development and making urban comparisons is through demographic measures—city population size or population density. However, these measures are chosen because of their widespread availability across cities, not because they are most relevant to the environmental and social challenges that cities face. Globally-available land-based classifications also exist [17–20], but in these, ‘urban’ land is most often clumped into a single homogeneous class. This is in

contrast to vegetated landscapes, which are sorted into 13 (or more) different classes (globally). Just as deciduous forests differ from evergreen forests and savannahs from shrublands, a single ‘urban’ or ‘built-up’ class limits our ability to understand the unique assemblages of neighborhoods that make up urban areas, and their assorted, often uneven, impacts on human and environmental well-being.

In contrast to aggregate amounts of people or land, one aspect of urban development that is more directly linked to urban sustainability is urban structure. Urban structure describes the mix and configuration of building forms, land parcels and uses, and grey, green, and blue infrastructural elements [21]. Different structures shape water, carbon, nutrient, and energy cycling differently [22–25]. For example, canyon geometries [26–28], greenspace configurations [29, 30], and street network patterns [31, 32] mediate the amount of solar radiation absorbed and emitted by the built environment, influencing the severity of urban heat islands [33–35]. Patterns of vegetated and impervious surface cover within urban areas regulate surface water flows and infiltration, moderating the prevalence of flooding [36] and environmental degradation from stormwater runoff [37]. The configuration of urban greenspace influences the quality of habitats, impacting urban biodiversity and species movement [38, 39].

In addition to physical and ecological functioning, urban structure shapes human processes and behaviors. For example, many studies have shown that dense, mixed-use neighborhoods, with connected street grids encourage more walking and biking [40–42], reduced driving [43, 44], and to a lesser extent more social interaction [45–47]. Regular increased physical activity can lead to a myriad of health benefits for urban residents—reducing the risk of hypertension, diabetes, colon cancer, cardiovascular disease, and obesity [48], as well as lower prevalence of mood and anxiety disorders [49, 50]. Furthermore, walking, biking and curbing car travel have environmental benefits, reducing air pollution and greenhouse gas emissions.

Despite the relevance of urban structure to biophysical and human processes, we have few systematic characterizations of urban structure that are comparable both within urban areas and across regions of the world. Population density is the most commonly used proxy for urban structure, though the distribution of people has been shown to poorly represent land and infrastructure configurations [51–53]. Administrative boundaries (e.g. voting districts, postal codes, census tracts), which are drawn based on governance units and population numbers, not structural similarities, lack standardized and comparable definitions across countries and regions, making scientific assessments difficult. A characterization of urban structure based on objective measures of the urban environment would complement these demographic-based approaches,

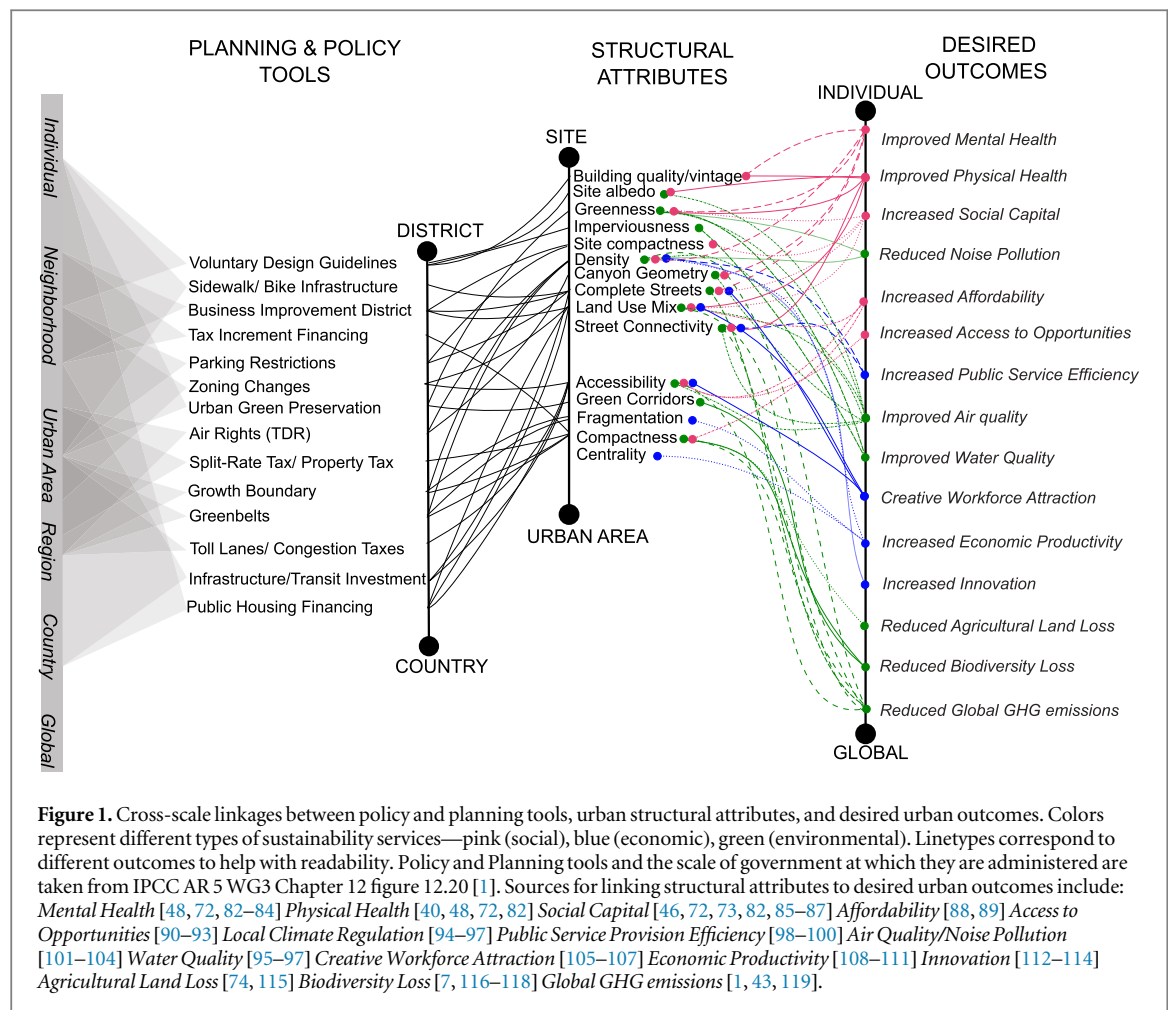
adding a new criteria for identifying like-areas where biophysical and human processes are sculpted in similar ways.

Classifying urban areas based on their structure is not new. Ecologists have recognized the importance of landscape structure for decades, and have developed several techniques for describing the patterns of vegetation, trees, and open fields within urban areas [54–56]. However, in these analyses, man-made elements (buildings, streets, economic land uses) have remained a single undifferentiated class—the class that fragments and encroaches on the natural land. ‘Structure’ in these studies encompasses the configuration of green landscape elements, with the built elements (the characteristically ‘urban’ elements) relegated to the background. As such, these approaches are more ecological in focus than urban, limited in their description of the variety of landscapes that make up an urban area, and their assorted, often uneven, impacts on sustainability.

Recently, two notable frameworks that advance the classification of built aspects of urban landscapes have been developed. First, the High Ecological Resolution Classification for Urban Landscapes and Environmental Systems framework [23] differentiates between single and connected building structures in urban areas. Second, from the urban heat island literature, a local climate zone classification system (LCZ) [57] characterizes 17 structural urban classes that relate to climatology. The LCZ framework is based on the combination of four surface components of the urban landscape: height, compactness, surface cover, and the thermal reflectance of materials. These approaches have enhanced our understanding of certain aspects of urban structure [58, 59] and have enabled urban comparisons based on land surface temperature and urban heat island. However, it is unclear how or if these approaches could be applied to other human and biophysical processes. As such, they are limited in their applicability and capacity to inform more general urban structural assessments, and city groupings for sharing spatial planning strategies effectively.

Here we address these limitations, by developing a systematic classification schema for characterizing and measuring urban structure. We introduce new nomenclature to define the different spatial and relational aspects of urban landscapes important to human and biophysical processes. By characterizing urban areas as a collection of smaller units, instead of as a single aggregate, we can better understand the variety and distribution of processes within.

As an example, we operationalize the schema within 909 urban areas in the US, applying it to the social process of travel behavior. Travel behavior is chosen because it is a process that impacts multiple aspects of urban sustainability—e.g. emissions, air quality, and physical activity/health. The classification schema enables a comparison of urban landscapes



based on the different travel behaviors that occur within them.

2. Nomenclature to characterize urban landscapes

We conceptualize urban structure as a mediator through which spatial planning can shape interactions between infrastructure, humans, biota, and abiota. Figure 1 highlights the cross-scale interactions between policy and planning tools, the structural attributes they target, and urban outcomes. As shown, several outcomes are impacted by structural attributes measured at intermediate ‘neighborhood’ scales, between the building or site scale and the urban area aggregate. This intermediate scale is where the majority of daily routines, behaviors, and lifestyle decisions are made [60], a notion which has been termed ‘activity space’ in previous geography and environmental psychology studies [60–62]. The size of this space varies between individuals, but previous studies using GPS trackers and travel diaries have measured it to range from 10 to 80 sq km [63–65], an area larger than three Central Parks but smaller than the borough of Manhattan, New York. The human decisions based on this space shape multiple aspects of sustainability, and yet, this sub-

metropolitan scale is currently unintelligible in most current urban classification systems.

Our new nomenclature describes four components of urban landscapes at sub-metropolitan scales: (figure 2):

- *Independent attributes* independent attributes describe magnitudes, types, and degrees of elements in a urban landscape. Spectral reflectance, land use, and population density are independent attributes that are commonly used to characterize urban landscapes. These attributes can be assessed within a parcel, tract, or pixel without knowledge of neighboring parcels. Independent attributes are important for describing the composition of the urban landscape.
- *Inter-relational attributes* capture the spatial relationships, configurations, and arrangements between multiple elements in a urban landscape. Job-housing balance, for example, depends on the relative geography of employment centers and residences. Inter-relational attributes are important for capturing flows of water, energy, materials, and humans.
- *Attribute Stands* are structurally distinct sub-regions within urban areas. One urban stand is delineated

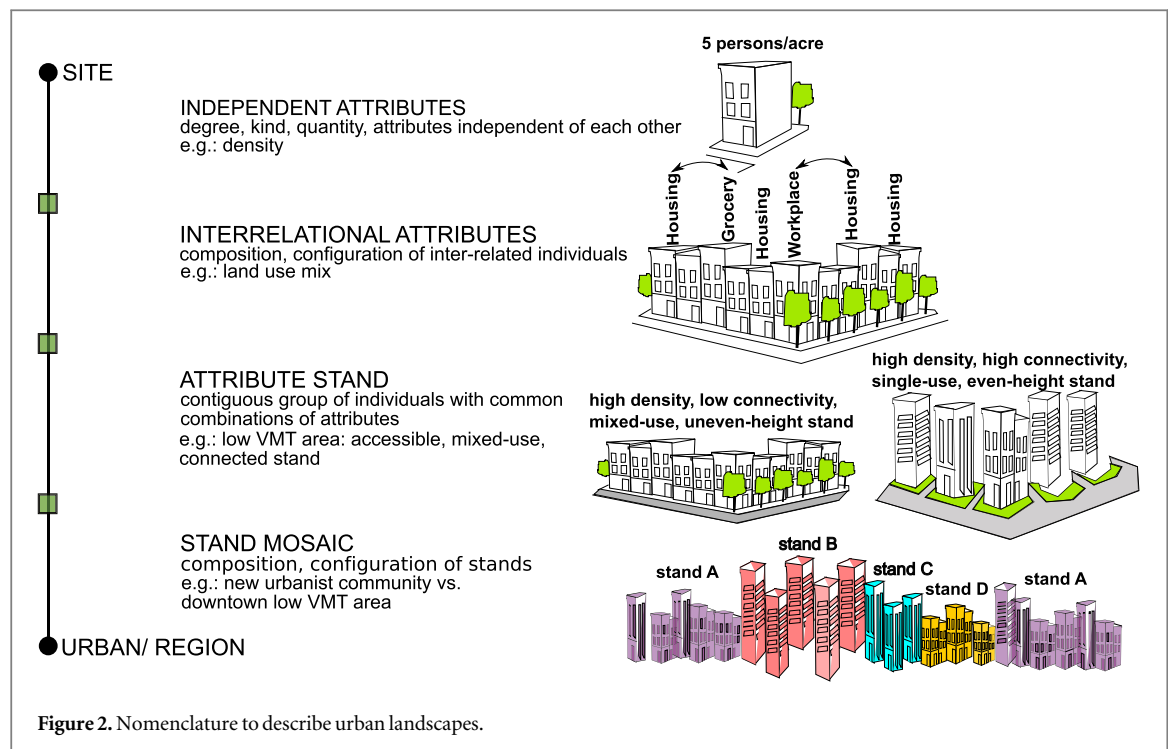


Figure 2. Nomenclature to describe urban landscapes.

from another by its like combination of shared independent and inter-relational attributes. The composition and configuration of natural and built elements within a stand is sufficiently uniform in type, magnitude, degree, configuration, and composition to distinguish it from adjacent stands in how it shapes sustainability processes.

- *Stand Mosaic* describes the composition and configuration of stands inside a boundary of inquiry (e.g. neighborhood, urban area, region). A stand mosaic can be characterized by the mix, layout, diversity, and dispersion of different types of stands within.

The idea of a stand is derived from forest science and management, where a contiguous community of trees, sufficiently uniform in composition and spatial arrangement, distinguishes it from adjacent communities [66]. Stands are standardized in terms of species mixes, tree sizes, and age so that they describe comparable units across a variety of regions and forest types. As such, they are designed to be useful for forest inventory, planning and silviculture.

Similarly, stands within urban landscapes describe land units that are sufficiently uniform in their structural composition and configuration, that they may benefit from similar planning and management.

3. Operationalizing the stand concept

As an example, we operationalize the stand concept for the social process of transportation behavior, differentiating between urban structures that influence travel differently. Empirical studies have shown that built-up intensity, street intersection nodal density,

job-housing balance, and job accessibility—a mix of independent and inter-relational attributes—can significantly influence travel distances and mode choices [1, 67]. We choose these four structural attributes as the criteria for defining transportation behavior stands.

Creating transportation behavior stands requires three methodological steps: (1) measuring the structural attributes, (2) creating stand ‘classes’ to describe different combinations of the structural attributes, and (3) spatially clustering contiguous areas of the same class. Details on each of these methodological steps is given in the appendix.

We first measure built-up intensity, street intersection nodal density, job-housing balance, and job accessibility at a high-resolution (along a 1 km by 1 km grid), using census, satellite, and GIS data. Built-up intensity is measured using the Global Human Settlement Built-Up Area Product [68], a Landsat-derived dataset that characterizes the spatial distribution of building footprints. Street intersection nodal density is calculated from the US Census Bureau’s 2014 Tiger-line road files [69] by summing the nodal degree of all street intersections in each grid cell. Job-housing balance is measured as a normalized difference index between the number of jobs (from US Longitudinal Employer Household Dynamics Survey [70]) and the number of residences (from the 2015 US Census block level population counts [69]) within a 3 km walkable radius of each grid cell. Job accessibility is measured as a distance decay function, taking into account the number of jobs in each grid cell [70] and the free-flow time-cost to reach those jobs from residences [69].

Once each of the four structural attributes is measured, they are used as inputs into an unsupervised

Table 1. Structural variance within and across US urban areas.

	Log(variance) of structural attributes				
	Access	Pop Dens	BU intensity	Street N.Dens	Job-H Bal
Across UA	21.4	11.4	3.5	4.21	−3.88
Within UA					
(quartiles)					
25%	15.9	11.85	4.24	6.35	−2.27
50%	17.39	12.35	5.23	6.64	−2.04
75%	19.26	12.90	6.12	6.93	−1.88
100%	26.43	16.12	8.84	8.10	−1.32

Note. For most structural characteristics (built-up intensity, street nodal density, and job-housing balance), variance in structure are greater within urban areas than between them. Sub-metropolitan structural characterization schema are needed to characterize this scale, where structural variety is largest.

k-means classification. Fourteen structural classes are created, defined by the class statistics listed in the appendix, table 1. Continuous grid cells assigned to the same class are combined to create new boundaries that delineate travel behavior stands.

Extensions of these analytical approaches can be applied to structural characterizations in different geographic contexts, that are connected to other landscape processes beyond travel behavior. We describe insights gained from this operationalization, for comparing urban areas and sharing strategies towards urban sustainability.

4. Results

4.1. Urban structural attributes

In the previous sections, we made the conceptual argument for why aggregate urban measures, like city population density, are inadequate to compare urban structure or share spatial planning strategies. In this section, we perform two empirical tests that test that argument. The first test examines scale: whether the structural variety between urban areas (measured with aggregate measures) is higher than the structural variety within urban areas. The second test examines whether population density characterizes the variety of structure within urban areas.

For the first test, we compare structural variance within cities with structural variance across cities. We averaged each measured structural attribute for all grid cells within each urban area to get average accessibility, job-housing balance, street intersection density, compactness, and population density. In table 1, the variance in these average structural measures across all 909 urban areas ('Across UA') is compared to the variance of the structural measures within each urban area ('Within UA'). The results (in log scale) show that 'within UA' variances are larger than 'across UA' variances for most structural attributes. For population density, built-up intensity, street intersection nodal density, and job-housing balance, within urban

structural variance was larger for at least 75% of the 909 urban areas (i.e. greater even at the 25% quartile). The majority of urban areas (50% quartile) had more than ten times the structural variance for those attributes within their urban boundaries than across urban averages.

Job accessibility is the outlier. There is more variance in job accessibility 'across UA' than 'within UA' for the large majority of US urban areas (98.2%). Job accessibility across urban areas is highly uneven because of differing economies and city sizes, which cause greater disparities in accessibility than within urban job disparities, between central business districts and the exurbs. Nevertheless, apart from accessibility, structural variety is larger between neighborhoods within one city than between urban areas in aggregate.

Our second test examines the ability of population density to characterize this structural variety in neighborhoods. In figure 3, blue dots represent all US neighborhoods with a residential population density between 2100 and 2400 persons km^{−2}. Though these neighborhoods have approximately equal population densities, the associated structures are highly varied. Combinations of normalized built-area intensity, job-housing balance, and street intersection nodal density span the attributional space. For instance, though the Houston-Midtown neighborhood in Texas and the Neighbors Southwest neighborhood in Beaverton, Oregon have similar population densities, the former is a mid-rise, connected, mixed-use area, while the latter is a low-rise, single-family, cul-de-sac community.

The differences in the structures of these two neighborhoods have implications on the activities of their residents. In Houston-Midtown, residents could meet many of their daily needs without relying on a private automobile, facilitated by high service densities and street connectivity. In neighborhoods like Neighbors Southwest, Beaverton, daily life requires car ownership and longer distances to access services and jobs. Thus, these two neighborhoods, despite their similar

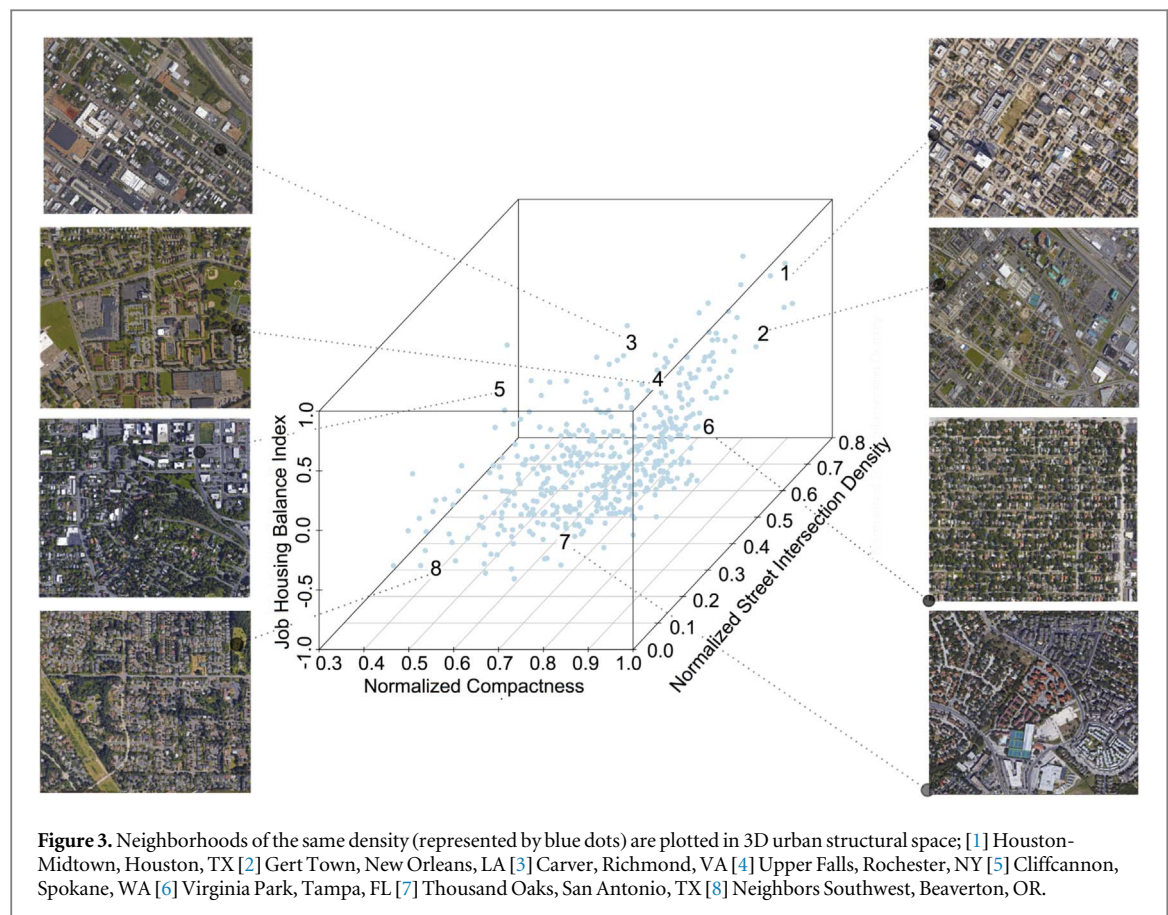


Table 2. Distribution of the urban population living in different stand classes in US metropolitan areas.

Stand class	% of UAs w/class	% of Pop within class
1: Large lot, individual exurban residential	49.07	2.5
2: Roadside, exurban residential	54.27	2.9
3: Large lot cul-de-sac residential	55.44	3.7
4: Large lot cul-de-sac residential near commercial	54.95	4.2
5: Medium lot, suburban	51.35	5.0
6: Commercial med lot strip development	47.89	5.7
7: Gridded, med lot, suburban residential	45.09	6.4
8: Commercial small lot development	40.24	7.1
9: Gridded, compact, residential	35.42	7.9
10: Gridded, compact, residential near commercial	30.3	8.9
11: Gridded, commercial dominated near CBD	24.53	9.9
12: Gridded, compact, mixed-use area near CBD	20.06	11.1
13: Commercial dominated mid-size urban core	10.47	15.5
14: Tight-grid, compact urban core	0.91	7.7

population densities, have divergent structures, and associated travel behavior implications.

Furthermore, equating structure with density constrains the strategies that can be considered for changing transportation outcomes. There are many viable policy and market instruments for transforming urban landscapes that bypass density altogether—for example, those listed in figure 1. Although population density is one of the most readily available measures for urban areas, it is not a sufficient catch-all proxy for

connecting to the broad swath of available travel demand reduction strategies.

4.2. Attribute stands

After using the structural attributes as inputs into a classification, 14 stand classes are defined. The classes span a structural gradient that ranges from the highly accessible, gridded, compact, mixed-use development of urban cores to the single-family, expansive patterns found in exurban development. We briefly describe

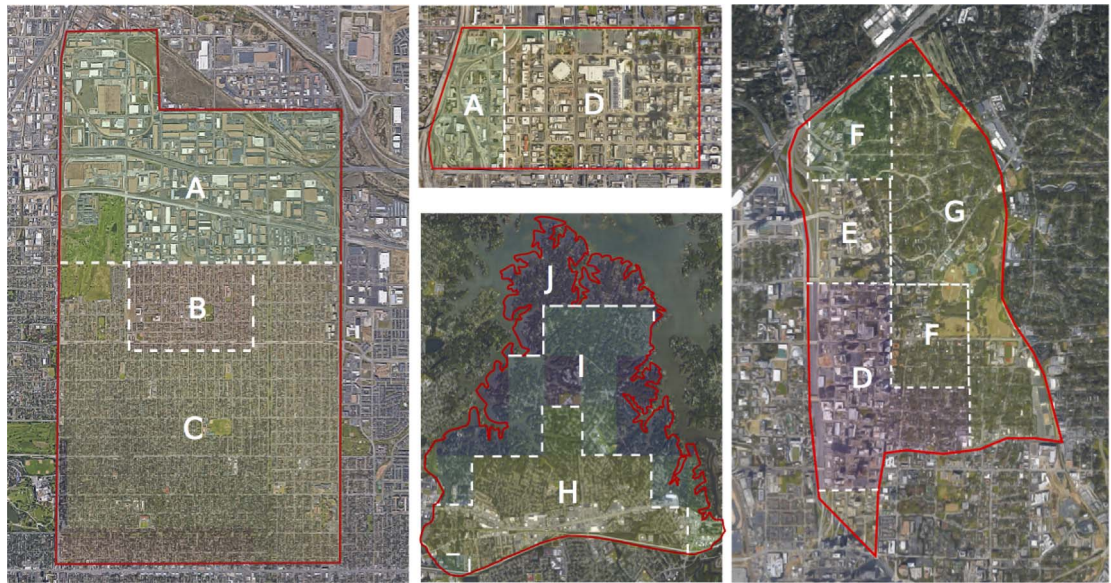


Figure 4. Neighborhood (red outline) are delineated into stands (white dotted areas) that have similar transport-relevant structural characteristics [left] Park Hill, Denver, CO [middle-top] Downtown, Salt Lake City, UT [middle-bottom] North Central, Virginia Beach, VA [right] Midtown, Atlanta, GA. Stands labeled with the same letter have similar street grids, lot sizes (compactness), access to employment, and job-housing balance.

these classes in (table 2), but more specific class statistics can be found in the supplementary material (appendix, table 1) available at stacks.iop.org/erl/14/045002/mmedia.

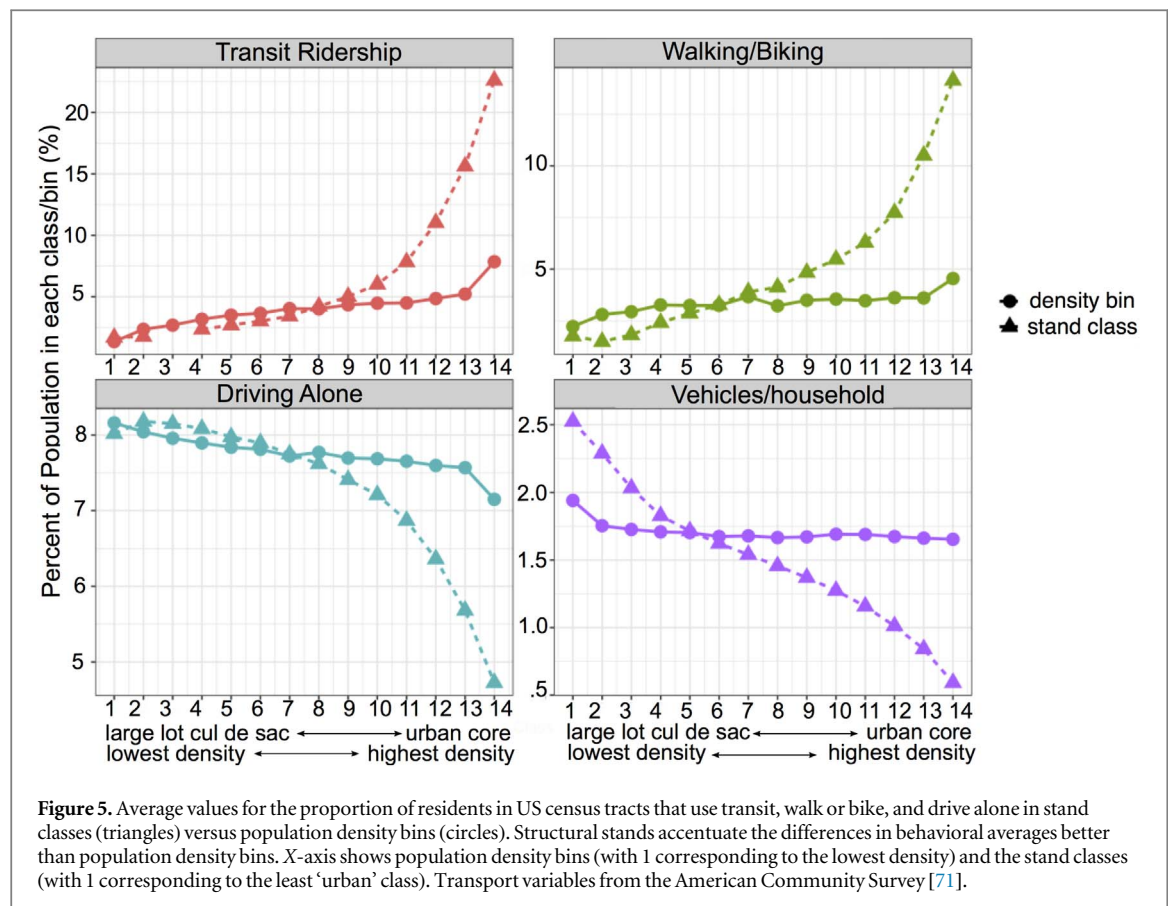
Stands are created by spatially clustering grid cells with shared structural attributes (i.e. in the same stand class). In the four examples in figure 4, each Zillow-defined neighborhood, outlined in red, consists of multiple types of stands, outlined in white dashes. Drawing these stand boundaries reveals three key points. First, the stand boundaries created did not align with any existing administrative or demographic boundaries. For example, Park Hill, Denver, Colorado consists of three different types of transportation stands: stand A (stand 11), a large-plot commercial and industrial zone, and B and C—two gridded single-use residential zones. Though B (stand 10) and C (stand 9) have similar local structural morphologies, B has higher accessibility to employment centers to the north. Stand boundaries are not redundant versions of existing neighborhoods, tracts, or other socially or politically defined units.

Second, even within neighborhoods, the stand mixture can be heterogeneous leading to local differences in environmental and social outcomes. For example, in Midtown, Atlanta, residents who live in stand D (stand 13) have access to more opportunities and services by foot or bicycle, leading to potentially lower transport emissions and commuting costs than those living in stand G (stand 5). In contrast, Midtown, Atlanta residents who live in stand G are surrounded by much more vegetation, which can aid in flood prevention and urban heat island mitigation. Instead of aggregating structural attributes along administrative

boundaries, the stand delineation enables a more direct connection between sub-metropolitan landscapes and the processes within them that shape environmental and social health.

Third, stand classes are not unique to a particular city, but are observed inside many US urban areas. Stands are based on absolute objectively measurable quantities: relationships between buildings, street intersections, employment opportunities, and residences. As a result, common stand classes can be found in different geographic regions—e.g. in figure 4, stand class A (stand 11) is in both northern Park Hill, Denver, Colorado and western Downtown Salt Lake, Utah. Similarly, downtown Salt Lake City and Midtown, Atlanta, though dissimilar neighborhoods when measured in aggregate, share stand type D (stand 13). Disaggregating the urban areas into stands is useful for identifying areas where similar landscape processes may be occurring, where similar spatial planning strategies or policies (e.g. those in the first column of figure 1) could be beneficial. The results show there is ample opportunity for strategy-sharing since many stand types are repetitive. On average, any particular stand occurs within 37% of US urban areas, though some stand classes were much more prevalent than others. For example, the stand class representing the densest skyscraper-filled urban cores of New York and Chicago was scarcest—occurring in only 1% of US urban areas but almost hosting 8% of the US urban population (table 2).

We use data from the 2010–2014 American Community Survey 5-Year Estimate [71] to examine how well stands capture heterogeneities in travel behavior, as compared to equally fine resolution population



density data. The American Community Survey tracks the proportion of residents in US census tracts that use transit, walk or bike, and drive alone. In addition, the survey tracks the number of vehicles per household—all behaviors that impact travel demand. Behavioral measures were averaged, in each stand class and in each comparable population density bin class. For all four of the tracked travel behaviors, variation between stand classes was more than three times as large as variation between the population bin classes (figure 5), indicating the structural stands better distinguish between areas with different travel behaviors than population density.

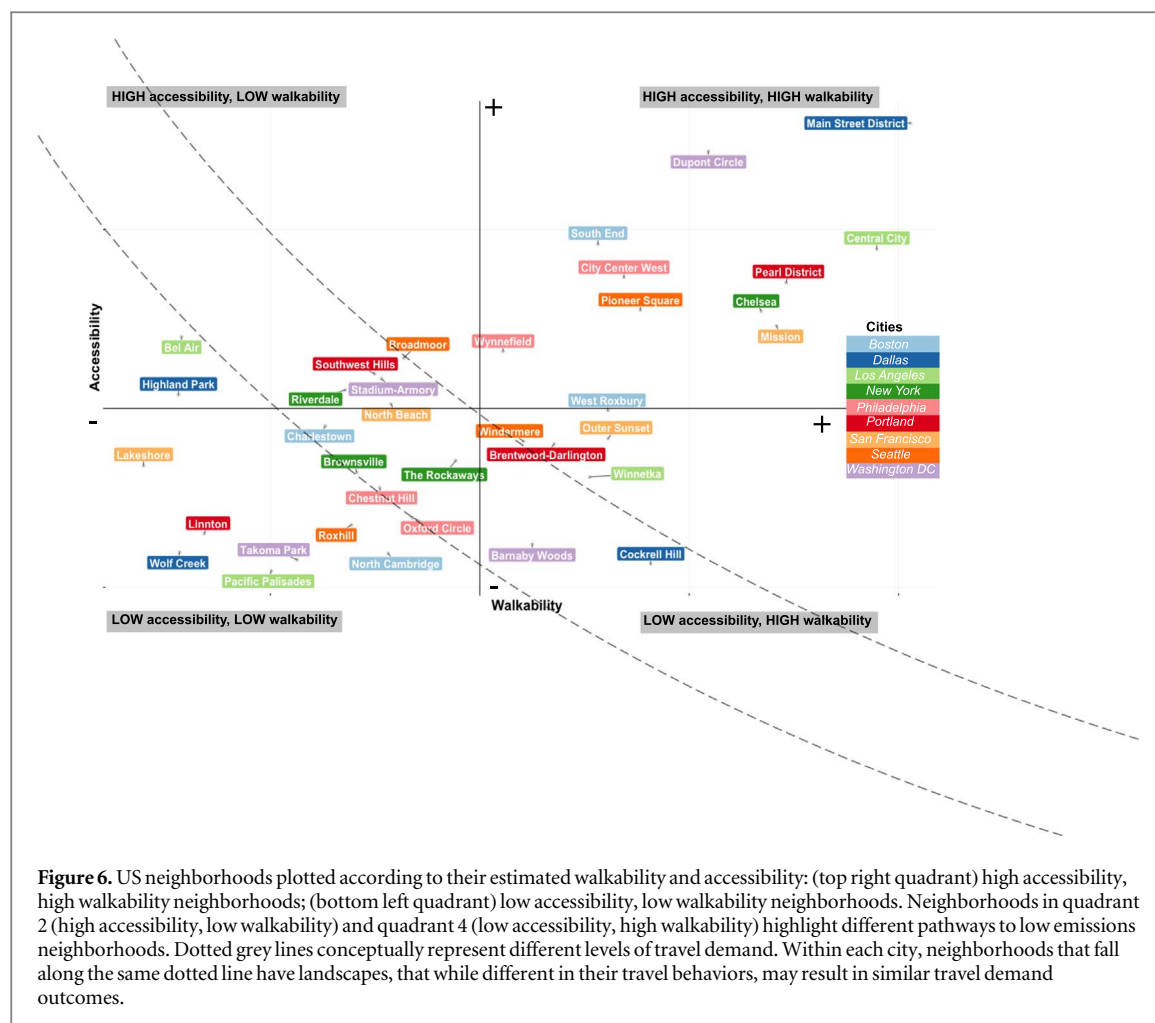
4.3. Stand mosaics

Though different structures can influence the same outcome, they may be responsive to different planning tools. For example, walkability and accessibility are two different structural characteristics that both influence private automobile travel demand (the outcome) through different processes. High accessibility stands enable shorter commutes to employment centers, lessening automobile travel demand. High walkability stands (those with a combination of high street intersection nodal density, building density, and job-housing balance) encourage pedestrian activity, also lessening private automobile travel. However, the planning tools that could help stands take advantage of their walkability potential (e.g. sidewalks, consolidated parking, street trees) differ from those that could

capitalize on high accessibility potentials (e.g. bus and transit stops, carpooling programs).

In this section, we analytically demonstrate the utility of stands for linking to spatial planning strategies. We plot normalized walkability and employment accessibility for a sample of neighborhoods in nine urban areas. We use neighborhoods here, instead of stand boundaries, because they have recognizable names, but the argument applies to stands as well. In figure 6, quadrants 2 and 4 contrast neighborhoods that may result in equivalent travel demand, but through different processes. For example, Southwest Hills, is a single-use neighborhood located close to the center of Portland, Oregon and adjacent to the interstate. Southwest Hill's location allows for short commutes to many of Portland's employment hubs, but locally, walkability within the neighborhood is low since the road infrastructure is disconnected and there are few services to frequent. In contrast, Brentwood-Darlington, a more mixed-use neighborhood comprised of a compact gridded street network, is walkable locally, but is a longer commute from Portland's primary employment centers. If this neighborhood characterization were based only on travel demand outcomes, Southwest Hills and Brentwood-Darlington would be likely be in the same class, even though the two neighborhoods could benefit from different planning and management strategies.

In addition to its relevance for planning and management, another benefit of the structural classification is it exposes co-benefits between different facets of



sustainability. Though we focus on travel demand here, walkability and accessibility also impact other aspects of ecological and human well-being. For example, walkable stands encourage physical activity [40, 48, 72] and may bolster social capital [46, 73]. In contrast, the co-benefits of higher accessibility could be spending less time and money commuting to work or greater job mobility. We would expect neighborhoods in quadrant 4 (like Brentwood-Darlington) to be more favorable in addressing human health objectives, while those in quadrant 2 may be more economically sustainable (Southwest Hills).

The composition and configuration of stands within urban areas creates a stand mosaic. Stand mosaics reveal novel information about the portfolio of stands within urban areas. We calculate how residents are distributed amongst these stands, and show the results for the largest twenty urban areas (figure 7).

The results show that stand mosaics provide new information on the structural make-up of cities that aggregate population densities obscure. This point was previously discussed at a neighborhood scale in figure 3, but is highlighted here again at the urban scale. As shown, New York's aggregate population density is comparable to San Jose's. However, the structures of New York and San Jose are significantly

different. Almost half of New York's population lives in the 'tight-grid, compact urban core' class (light pink), a class that does not even exist within San Jose. In this class, street infrastructure is highly connected, street blocks have high built-up intensity, development is mixed-use, and there is high accessibility to jobs, all of which lessens travel demand. New York also has a longer tail—with almost 10% of its population living in large lot low density residences. In contrast, San Jose is largely structurally homogeneous, more similar to Los Angeles or Riverside than New York. Aggregate measures disregard these distributional patterns, which often underlie the disparate environmental and social outcomes within urban areas.

The differences in structure between New York and San Jose speak to their different development histories. San Jose's population density is high, largely because of an urban growth boundary imposed in the 1990s in response to the city's rapid expansion. As shown in figure 7, only a small percentage of San Jose residents (<2%) live in blue and green classes—the assortment of large lot residential archetypes that are common at the periphery of American urban areas. However, though the growth boundary has driven infill development and increased population density, it has not changed the connectivity of the urban street

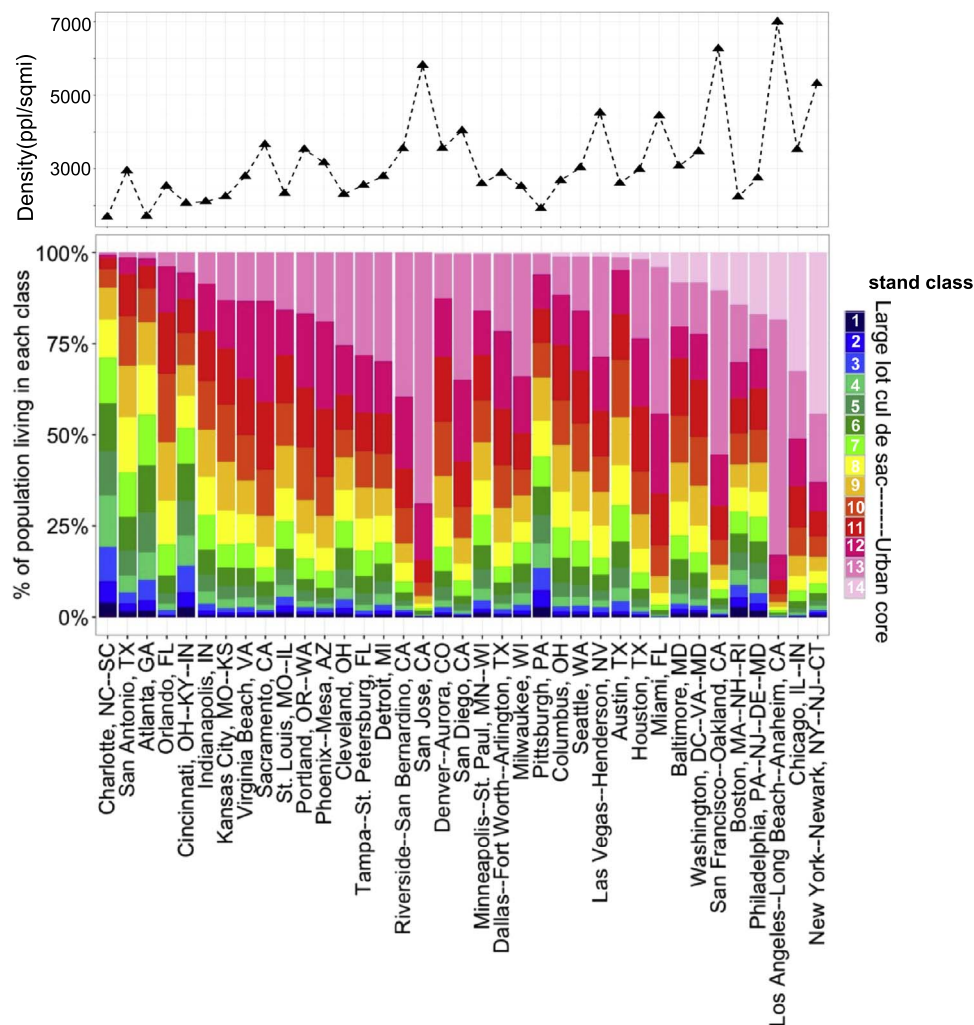


Figure 7. US cities with their portfolio of structural classes.

infrastructure or the precedent zoning practices. In contrast, New York envisioned its famous street grid in 1811—planning for growth—while it was still a town of only 100 000 people.

5. Discussion

Characterizing and measuring the structure of urban landscapes is a step towards comparing urban areas in a way that helps them share strategies effectively. Though there are many existing characterizations of urban landscapes [74], none are explicitly designed for this goal. Characterizations from the architectural and urban planning tradition generally measure the ‘form’ or ‘morphology’ of built infrastructure within urban landscapes to examine programming and design in the city for urban residents. Conversely, urban ecologists have generally focused on the green and blue infrastructure within urban areas, characterizing the sizes, shapes, and configuration of natural patches, but affording less attention to the built infrastructure (recent ‘ecology of the city’ [75] and MetaCity frameworks [76] are notable exceptions).

We have illustrated the importance of inter-urban characterization, showing that the structural variety within urban areas tends to be greater than across them. We demonstrated that population density, the most common means for comparing urban areas and neighborhoods, poorly characterizes landscape attributes—an observation that reinforces more qualitative approaches in previous work [51, 53, 77]. One important finding is that stands can capture the configurations of street networks and buildings, and the mix of employment and residences in a neighborhood that shape travel demand characteristics that density alone cannot measure or describe.

We use these observations as the underlying rationale of a structural classification schema for urban landscapes. The different components of analysis—from independent attributes to urban mosaics—add new language for describing the basic functional landscape units in cities, from the lens of sustainability.

For science, stands create opportunities for devising a sampling strategy. If stands are mapped, surveys examining relationships between landscape patterns and human and environmental processes can be

representative. Instead of relying on case studies, representative samples of stands enable generalizable results. Much of the previous research linking urban landscapes to urban outcomes has been developed from studying cities in the United States and Europe [78], so new strategies for broadening this pool of work are needed. In an era of massive and rapid urbanization transformations, findings that can be extrapolated across geographies, to similar stand types, can help science, policy, and practice keep pace with the need for timely urban development and redevelopment guidance.

For policy and planning, urban stands create a way to correct scale mismatches between urban outcomes and the governance units managing these outcomes. Administrative boundaries do not indicate substantive functional differences and are divorced from the sustainability processes that occur within them. A structural characterization of urban landscapes can link more directly to strategies and planning tools. As foresters prescribe a particular set of silvacultural techniques to each forest stand—city governments can more strategically target appropriate spatial policy, planning, regulation, and market instruments to specific urban stands, instead of city-wide. This could increase the effectiveness of policy and planning interventions, and also make them more cost-efficient since their application would be targeted.

Further, there are instances where the processes causing poor urban outcomes are a collective-action problem—requiring cooperation across multiple cities (e.g. maintaining good air quality, biodiversity protection, or mitigating emissions), while the processes that shape these outcomes are altered by policies applied to sub-metropolitan landscapes. Since the same stand types are commonly found in multiple regions, collectively cities can share strategies more effectively across vastly different geographies, scaling up their impact. This kind of collaborative response could expand the solution space for some global environmental problems, like climate change, where capitalizing on the (still insufficiently understood) aggregate potential of spatial planning has seemed unrealistic, because of the diversity of landscapes and actors involved. Leveraging the larger impact of shared spatial planning strategies, city coalitions may engage broader financial and institutional support not usually available for a single neighborhood (e.g. the UN Sustainable Development Goal fund).

Tracking changes in the composition of urban mosaics would add value for global policy discourse on urban development as well. The urban UN Sustainable Development Goal, for example, has collective targets for cities (e.g. ‘reduce the adverse per capita environmental impact of cities’ or ‘enhance inclusive and sustainable urbanization’). Existing indicators for monitoring the sustainability of urban development (SDG 11.3) are based on land use efficiency—land consumption rates divided by population growth

rates. While this metric captures the growth of urban extents and links to environmental issues related to land subsumed by urbanization, it does not capture the structure of neighborhoods built within urban boundaries, nor their related social or environmental impacts [79]. Monitoring stand mosaics would add new valuable information about the landscapes being built and changed in urbanizing cities. In addition, stand mosaic characterization responds to three scientific gaps highlighted in the recent *Nature Sustainability* expert panel report, Science and the Future of Cities: (1) the need for more empirically systematic studies of urban areas (2) that cover a wider variety of urban areas and (3) a larger sample of urban areas [80].

6. Conclusion

The proposed classification schema is general, operationalized for travel behavior across US urban areas, but meant to also be applicable to other geographies and other processes, such as those that impact water quality, human health, or climate vulnerability. We could imagine, for example, simultaneously considering travel behavior stands with urban heat island stands (similar to those developed through the LCZ framework) [57]. By overlaying the two, areas where emissions mitigation and climate adaptation should be prioritized, as well as where spatial planning may be able to devise mutually beneficial structural solutions.

Towards the aim of extrapolating the stand concept to other sustainability processes, there are some important prerequisites: the existence of fine-scaled spatial data for mapping urban landscapes and theory that describes what aspects of structure shape these processes. The availability of each is dependent on the processes and geographies in question. Remote sensing and volunteer-contributed vector datasets, such as Open Street Map, have widened the availability of high-resolution data for measuring structure, including brand new sources and methods for extracting the urban verticality and building heights [81]. However, currently there are still spatial and temporal limitations to remotely-sensed datasets. For example, the Global Human Settlement Layer, which measured compactness, was limited in its spatial resolution to 100 m, and is only available for 1975, 1990, 2000 and 2014.

For this study, we also used demographic census data on population and job distributions as inputs—which are currently less available in countries with poor statistical collection systems. Some attributes important for sustainability that are not observable from satellites may still need to rely on piece-meal surveys, making standardization difficult, and measurements of structural changes across time unfeasible.

To our knowledge, there is no existing classification schema for urban landscapes that have been devised to help manage urban areas towards

sustainability. Characterizing and measuring the urban landscape as a collection of different process-based stands can change the basis for urban comparisons and monitoring. ‘Like’ stands in different geographies could benefit from the same spatial planning strategies, creating new partnerships. The classification schema and results presented here are a first step towards making these connections. The application of this schema to multiple sustainability processes across cities can lead towards a systematic understanding of the potential of urban development and redevelopment to guide urban transitions towards sustainability.

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