Cities 151 (2024) 105079

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Searching for the DNA of urbanisation. A material perspective

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ARTICLE INFO

Keywords:
Urban development
GIS spatial analysis
Sprawl
Industrial ecology
Technomass

ABSTRACT

Broadly accepted categorical differentiations of urbanisation understand cities as well-defined objects containing urban spaces in contrast to their hinterlands. However, urbanisation's multidimensional complexity challenges these approaches in the context of increasing social issues marked by rapid urban expansion, uneven development, ways of life, inequality, commodification, etc., that require fresh scientific answers grounded in innovative empirical evidence. Here, we analysed the population-based and the land-use/land cover-based categorical understandings of urbanisation, looking at their origins and main shortcomings. Our analysis makes a generalised description of urbanisation's spatial complexity, with an emphasis on the problematic spatial delimitation of urban boundaries; urbanisation occurring in remote wild areas; and the missing third spatial dimension. We discuss these shortcomings based on recent scientific developments, providing reasons why the categorical approach needs to be changed and how. We propose a continuous indicator of urbanisation which is based on the accumulation of anthropogenic materials, a physical, rather than a spatial or demographic characteristic. Our proposal allows the analysis of socio-ecological systems' spatial organisation, pursuing comparative studies across geographies and times, informing globally generalisable patterns of urbanisation processes and giving a material body to address claims for sustainable urban development.

1. Conceptual grounding

What is urbanisation? Most often it has been understood as a process of population shift from rural to urban areas. This very simplified understanding, however, is complicated by conceptual imprecisions – in spatial, thematic and temporal terms. This unclear conceptual foundation upon which the urban analysis apparatus is built has been posing tremendous practical challenges to urban research for decades (Castells, 1977), without substantial improvements reflected in how urbanisation has been conceptualized and measured (Bai et al., 2017).

A stronger conceptual grounding of urbanisation remains a shared claim across different urban epistemologies, from archaeology (Ortman et al., 2020; Smith, 2015) to urban ecology (McPhearson et al., 2016; Pickett & Zhou, 2015), while searching for clarifying effects on the practical side of urban research (Brenner & Schmid, 2015). On the one hand, in disciplines such as urban studies, urban economics or urban planning, urbanisation is understood as an exclusive social phenomenon (Batty, 2013; Storper & Scott, 2015) without any ecology. However, in the context of increasing social issues marked by uneven development, inequality, ways of life, commodification, etc. the multidimensional complexity of urbanisation challenges such a socially biased urban analytical apparatus. To tackle such challenges, we call for fresh scientific evidence to advance meaningful scientific answers. On the other hand, increasing global issues and scientific concerns about manifold ecological problems, including climate change, land consumption and degradation, pollution, loss of biodiversity and ecosystem services, etc., have been linked with urbanisation (Haase et al., 2018; Seto et al., 2016). These negative ecological effects are evidencing that urbanisation cannot be considered purely as a social process. We claim here that re-examining the theoretical grounding is in demand to provide new innovative conceptualisations enabling better integration of social and natural sciences. This integrative approach can be central to advance urban research and providing meaningful answers to the current environmental crisis. The pathways for addressing these environmental challenges require changes in the current way of conceptualising the relationships between socio-cultural constructions – i.e. the concepts used to understand reality- and material processes – and the idiosyncratic phenomenologies possible to observe (Hornborg, 2001).

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https://doi.org/10.1016/j.cities.2024.105079
Received 19 October 2023; Received in revised form 25 April 2024; Accepted 29 April 2024
Available online 11 May 2024

Current conceptualisations of urbanisation have relied on broadly accepted categorical differentiations in which cities are conceived as well-defined objects containing urban spaces and in contrast -in terms of drivers and processes- to their hinterlands, the so-called rural areas. Conceptually speaking, these categories reflect the Western intellectual tradition's bias of isolating society from nature (Alberti et al., 2003; Lin et al., 2012; Young, 2009). Thus, empirical studies are biased towards spatiality. The attempts to find urban boundaries fail in this conceptual trap, which is resolved by using context-specific spatial assumptions that are limited to performing comparisons across different geographical settings or historical times. Such spatial units, whether generated administratively or data-driven, have their idiosyncratic justifications. They serve as the basic information vehicle for scientific research, policy development and planning processes. These spatial reference units are operationally so powerful that they shape the current understanding of urbanisation. However, grasping the full picture requires looking beyond such specific 'urban' spatial units because the impacts and dependencies arising from urbanisation go far beyond the limits of such urban spatial units. Furthermore, current spatial empirical attempts do not unveil the true continuous spatiotemporal nature of urbanisation (Inostroza et al., 2019) involving not only a social but also an ecological dimension that are both shaped in a very material sense. The DNA of urbanisation, what makes urbanisation possible as such, is what we discuss in this piece.

The remainder of this essay is as follows: Firstly, we refer to the population-based and land-use land cover-based understandings of urbanisation. The emphasis here is on how the categorical understanding arises and why it needs to be changed. We revise the complexity and challenges posed by urbanisation. These reflections, which are based on empirical findings, discuss mostly the shortcomings of using categorical variables to define urbanisation; spatial complexity, with an emphasis on spatial delimitation; urbanisation occurring in remote wild areas; and the missing third spatial dimension of urbanisation. In Section 3, we provide an overarching analysis of the morphogenetics of urbanisation, to illustrate the relevance of its material structure. This overview provides the basis for an analysis of urbanisation with a focus on the material dimension, which is discussed in Section 4. We conclude that rather than the spatiality or the demography, urbanisation requires a particular materiality, and it is here where the DNA of urbanisation is to be found.

2. The urbanisation we know and measure

Over the last 50 years, the understanding and measurement of urbanisation has mostly relied on population change. The second approach used to analyse and measure urbanisation comes from spatially explicit sciences, such as GIS and remote sensing, in which the definitory aspects are land-use/land-cover change (LULCC).

2.1. Urbanisation as population change

The demographic understanding of urbanisation was first proposed by King Davis, an American sociologist who developed a systematisation of global population statistics. Over this basis, the UN population statistics were developed (Brenner, 2013) using administrative borders that often do not match urban areas' physical extension. Furthermore, to differentiate what is 'urban' and what is 'rural', the demographic approach requires cutting population values that each country defines arbitrarily. Indeed, there is a large variability of the threshold values separating urban from rural settlements (Inostroza & Zepp, 2021; Taubenböck et al., 2019). For instance, in some Latin American countries, the population threshold for an area to be considered urban is 2500 inhabitants; in other countries, the threshold is 5000 inhabitants; and in India, the threshold is 100,000 inhabitants. Such a definition of what urban is leads to inconsistent, non-comparable statistics originating measurement problems (Inostroza et al., 2019; Taubenböck et al., 2022). Surprisingly, such statistics are today broadly cited in almost every article dealing with an urban issue.

In a strictly phenomenological sense, there is nothing special about these population values: our current understanding of urbanisation remains without a clear analytical distinction. Rather than being an empirical fact, what is today called 'urban' is floating on thin air. Such arbitrary demographic assumptions leave the most common sentence currently used in scientific articles -"today more than 56% of the population is urban"- meaningless, without analytical power to define urbanisation. Criticism of the demographic approach to urbanisation dates back to Castells, who, more than 50 years ago, called this approach "the statistical empiricism in the delimitation of the concept of urban" (Castells, 1977):10). The ground for new conceptualisations of urbanisation needs to be fertilised with fresher innovative concepts.

2.2. Urbanisation as a Land-use Land-cover change

Land-use Land-cover change (LULCC) is considered a key aspect of urbanisation (Bai et al., 2012; Grimm et al., 2008). Thus, LULCC methods are commonly used in spatiotemporal assessments of urbanisation (Grimm et al., 2008; Schneider & Woodcock, 2008). From this strict operational perspective, land can be classified as urban or non-urban by using a Boolean approach, which leads to a categorical description of urbanisation that does not allow for direct quantitative comparisons between different geographies and time (Inostroza et al., 2019).

Homogeneous land cover patterns are obtained using remote sensing methods that delineate discrete land units that compile several land surfaces in a categorically coarse manner (Anderson et al., 1976). This is the approach used in broadly known data sets, like the Corine land cover (https://www.eea.europa.eu/publications/COR0-landcover) the Urban Atlas (https://land.copernicus.eu/local/urban-atlas), the Global Human Settlement layer (Pesaresi et al., 2013), the Global Urban footprint (Esch et al., 2012), or Local Climate Zone classifications (Bechtel et al., 2015; Zhu et al., 2022). These datasets use the same homogenization principle to combine artificial and natural surface types, classifying space into different categories that are mutually excluding. The problem lies in classifying space rather than measuring phenomenological changes continuously.

2.3. The shortcomings

Urbanisation has been understood based on urban and rural spatial classes. Such categories describe a set of idiosyncratic features found in particular places that are considered mutually exclusive. These categories cannot describe the continuous spatial complexity of urbanisation, hiding the multi-scale and multidimensional interrelations of urban cores, peripheries, hinterlands and more. Thus, these categories are not an adequate measure of urbanisation with all its dependencies in time, space and processes (Inostroza et al., 2019). They remain as common categories and also important landmarks in political and planning discourses (Parr, 2007). In science, it is also a common strategy to use categories to provide a better understanding of complex physical phenomena. One can understand this as a permissible tool to make the complexity of the world tangible. For instance, scientific disciplines addressing temperature make categorical qualitative statements like hot or cold. However, to measure temperature, we use a continuous scale and unit—Celsius, Kelvin or Fahrenheit degrees—for which science provides frameworks to perform such measurement trivially. In the measurement of urbanisation and its spatial complexity and impacts, a truly continuous measurement based on a physical -i.e. material- property is still widely missing. In consequence, urbanisation's DNA in a material sense is missing in current analysis.

A scientific measurement of urbanisation does not need to find an urban space in opposition to a rural one, but rather to measure the urban intensity on a continuous scale. That is a scientific outcome that can serve as a basis for further analysis, where categorizations might fall out of what can be properly called scientific and be more appropriated in a policy context (statistical urban for instance).

The categorical understanding of urbanisation is challenged by three overarching features: (1) urbanisation does not follow strictly monocentric urban development patterns but rather a dispersed manner. With it the standard administrative and spatial definitions used to measure urbanisation are blurred at several scales (Brezzi & Veneri, 2015; Kloosterman & Musterd, 2001); (2) urbanisation is not constrained to urban areas and their hinterlands but rather spreads over all types of landscapes, including remote areas, where it is found in completely different spatial forms of anthropogenic alterations and modifications (Parry et al., 2014; Salgueiro Barrio & O'Shea, 2022); and, (3) urbanisation has a fundamental third spatial dimension normally unacknowledged in standard population or LULC-based approaches due to the bi-dimensionality of the used indicators (Nichol et al., 2013).

2.3.1. Blurred urban limits

The limits of administrative urban areas do not reflect the real area covered by cities and therefore can mislead any space-based calculations like population density or per capita green areas. Commonly, administrative areas might include large agricultural and forest land and some other surrounding natural areas biasing comparative approaches between different cities. Indeed, the mismatch between the physical extension of cities and the respective delimitation of administrative units (Fig. 1) biases spatially based comparisons (Taubenböck et al., 2019). Fig. 1 illustrates this mismatch where neither the administrative area of the metropolitan municipality nor of the province follows the settlement patterns. To avoid these shortcomings researchers should delineate the real extension of the urban area before performing spatial assessments (Kabisch & Haase, 2013).

Research studies dealing with the urban heat island (UHI) effect provide another good example: The UHI accounts for the difference in temperature between cities and their hinterlands (Oke et al., 2017). Here the causality of the UHI lies in the physicality, such as high building density, paved surfaces, building materials, etc., that do not match the peripheral urban spatial units. To avoid this methodological shortcoming, the continuous urban fabric must be strictly separated, before spatial indexes for analysing the UHI or green space patterns are estimated). The use of administrative units without the spatial delimitation of the physical extension of the urban continuum brings relevant bias to urban analysis, whether for urban expansion, green space, UHI, or many other aspects.

2.3.2. The urbanisation of the last of the wild

The planetary scope of urbanisation makes the current urban-rural categorical differentiation highly insufficient for describing its spatial structure and the urban colonisation of remote wild areas. This categorization introduces an incompleteness or even a bias to analytical results related to the common conceptualizations of a spatial urban category.

Qualitative and quantitative spatial analysis understands urbanisation as a dichotomy between LULC classes, where economic activities not located in cities are not considered to be urban. For example, current

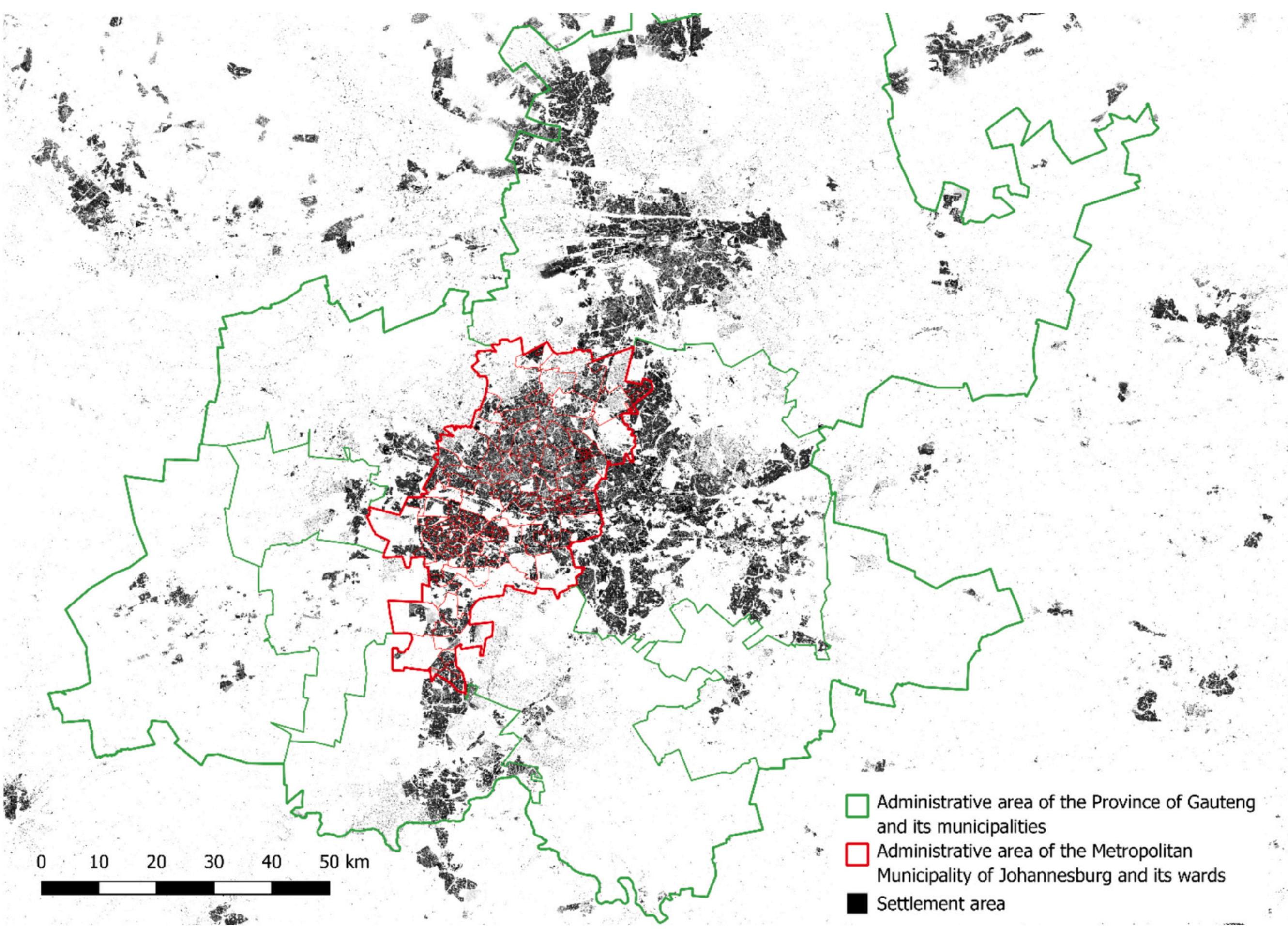

Fig. 1. The province of Gauteng and its municipalities.
Source: Administrative units are taken from the GADM - Database of Global Administrative Areas data (2018), the settlement areas are taken from the Global Urban Footprint mapping product (Esch et al., 2012), own elaboration, unpublished.

land systems science does not classify mining camps, isolated industrial complexes, industrial farming, refugee camps, small settlements, roads, etc., as urban land use categories, as can be seen in analyses of low technomass amounts linked to urbanisation degrees, as illustrated in Fig. 4. But these are places where the urban process is co-determined materially, economically, ecologically, but also socially and politically. Thus, the current understanding of urbanisation is simplifying the multi-dimensional relations of the urban on local to planetary scales.

2.3.3. The missing third spatial dimension

Common urbanisation assessments rely mostly on 2-D LULC indicators where patches of LULC are used to describe spatial heterogeneity (Forman & Godron, 1986; Forman, 2014; Zhou et al., 2017). While these assessments only use one or two spatial dimensions, urbanisation as a process unfolds in three spatial dimensions and time (Wentz et al., 2018).

From a phenomenological perspective, the 3-D traces of urbanisation are to be found in buildings but also in technological infrastructure including roads, train tracks, electrical lines, water and sewer pipes. These are on the contrary cartographically reflected in one dimension and thus difficult to include in spatial analysis vis a vis dominant 2-D entities (Inostroza et al., 2019).

Increasing attention has been given to building density in its 3-D representation which has produced interesting findings (Lin et al., 2012, 2020). However, to date, these studies mostly remain at a non-multi-temporal stage. To continue in this promising direction such attempts should take a stronger compromise with real continuous measurement, abandon the replication of urban-rural dichotomies, and work towards 3-D multi-temporal studies. Nowadays, artificial intelligence can substantially contribute to 3-D and 4-D analysis and calculations.

3. The material spatiotemporal behaviour of urbanisation

In the previous section, we have analysed the conceptual and operational shortcomings of current standard approaches to urbanisation. What is at the core of urbanisation? Where can we find its DNA, the structure determining its reproduction and perpetuation in time? According to (Scott & Storper, 2015), the core of the urban definition is "the urban land nexus". While this approach brings space as a fundamental component of the urban definition, it does not provide any clue for its measurement, remaining trapped in the spatiality that we have criticized in Section 2. Furthermore, space is a high-level abstraction that doesn't allow for the necessary inclusion of qualitative change that is fundamental to understanding urbanisation and its impacts, and the underlying ecology that follows the laws of thermodynamics. We acknowledge that urbanisation is materialized in space, and relates to transformations of ways of life, and social or economic structures, among other issues (Nassehi, 2002; Tonkiss, 2013) encompassing a complex, even confusing morphology. Fig. 2 shows examples of urban complexity unfolding in manifold different urban forms in different places around the world. Such great morphological complexity makes it difficult to derive generalisable results or comparisons. For instance, in the case of Trento's surroundings such urban morphology might be archetypical for northern Italian landscapes but not necessarily generalizable to all European landscapes.

While built-up structures encompass paramount volumes of anthropogenic materials that are accumulated and remain for decades or centuries, we argue that the morphogenetics of urbanisation produces a context-specific material structure, archetypical material assemblages composed of infrastructures and buildings, that precede and underpin other development forms. This materiality is a common characteristic of urbanisation across historical times and geographies that has been measured even in archaeology (Ortman et al., 2020). All these different kinds of humanly processed matter are what we call 'technomass'

Fig. 2. Urbanisation possess a particular phenomenology. Examples from different cities.
Source: own elaboration, unpublished.

(Hornborg, 2001; Inostroza, 2014). Entangled with all types of designed and remnant green space, they account for the very urban material structure, that follows a set of regularities (Lemoine-Rodríguez et al., 2020; Ortman et al., 2020). The following section looks at the material spatiotemporal behaviour, i.e., how the material structure unfolds in space and time, in short (inner) and long (extended) distances.

3.1. Omnipresent urban expansion made of matter

Urban expansion is currently one of the most powerful forces modifying landscapes, spreading around existing urban cores, developing in a polycentric manner, or spreading out at larger distances (Angel et al., 2011; Taubenböck et al., 2012). Urban expansion is a spatial process that implies the increase of the physical size of cities—surface under a 2-D approach and material stocks under a 3–4-D approach—into surrounding land areas.

While urban landscapes feature regional or cultural specifics (Taubenböck et al., 2020), the arising expansion patterns are common and lie beyond social or cultural context and have been characterized as a global homogenization of urban form (Lemoine-Rodríguez et al., 2020). At the same time, urban expansion implies a permanent increase in the built-up material structures that make up the body of urbanisation. Materials have been acknowledged as one of the six fundamental components of urban form (Wentz et al., 2018). Furthermore, the expansion of urban areas implies a direct higher, faster consumption of raw materials that are accumulated in old and new urbanised areas but also in natural landscapes (see next section).

It stands to reason that there is a direct link between urban expansion and their respective material accumulation rates and volumes. This has, however, not yet been acknowledged neither by urbanisation studies nor by urban metabolism analyses that considers urban systems to be in a steady state concerning mass and energy (Baccini & Brunner, 2012). We argue that traditional assessments of urban expansion should be linked with urban metabolism analysis to ascertain the dynamics of material accumulation at the local, regional, or even planetary scales and interrelations.

3.2. The extended urbanisation found in the last of the wild

Buildings, roads, infrastructure, machines, etc., are the material characteristics of urbanisation regardless of their location, even considering that they are spread across the whole Earth. Indeed, while different material intensities are to be found all over the world, many of them are not considered properly urban, like mining camps and isolated infrastructures (Brenner, 2013; Inostroza & Zepp, 2021). However, there is an extended type of urbanisation that makes resource extraction possible in locations that are far away from urban cores and is occurring even in remote areas of the world. Urban areas are always connected to areas of resource extraction through particular economic activities (Inostroza, 2018; Inostroza & Zepp, 2021). Classifying the urban tissue as an ultimate and independent attribute of space neglects its entanglement with the non-urban ecosystems providing the material basis for urban life.

This broad scope of dispersed urban fragments belongs to a planetary urban fabric that connects even the remotest places to an urban network of material and energy flows mediated by monetary transactions (Inostroza & Zepp, 2021). Analysing the traces of urbanisation in remote areas using the background of industrial ecology will acknowledge where energy and materials consumed in urban areas come from. The extended urbanisation is both, an urbanisation pattern in itself and the necessary condition that allows the building, sustaining and reproduction of the urban space.

3.3. The production and reproduction of the urban material structure

Spatially, there are regularities followed by urban systems all over the world. In the process of urban expansion, homogenization of urban form has been observed (Lemoine-Rodríguez et al., 2020). However, looking at the materiality of urbanisation patterns, it is possible to observe profound socio-ecological asymmetries emerging within urbanisation, either in the materiality of the grey or the green (Fig. 2). Such asymmetries have been addressed in a large body of scientific literature concerned with environmental justice, inequality, informality and the like (Behrens & Robert-Nicoud, 2014; Castells-Quintana & Royuela, 2015; Kabisch et al., 2017). Urbanisation is internally a process of spatial differentiation, what (Scott & Storper, 2015) have called the urban land nexus, that segregates different social classes with distinctive materiality. Both processes occur simultaneously producing a combination of materials in specific volumes, rates and intensities that ultimately give rise to the apparently unique but fundamentally similar urbanisation patterns seen in different parts of the world and even historical times (Lemoine-Rodríguez et al., 2020; Ortman et al., 2020). For instance, technomass would allow the identification of trends and specificities of urbanisation concerning disparities between regions due to differential material means resulting from natural capital availability, trade and institutional capacities, technological development and levels of social complexity, among others. Such an approach could bring light to pivotal periods like the last century, a period marked by planning analyses and regulations prevalent across the world.

Indicators linking these two contradictory aspects, the spatiality, and the materiality of urbanisation, are operationally needed to unveil the regularities and homogenization of urban form (Lemoine-Rodríguez et al., 2020). At the same time, however, it is needed to consider the socio-ecological asymmetries that are produced. We argue that indicators integrating the spatiality as bounded to the materiality reveal the urbanisation's DNA. Furthermore, materials have a lower degree of abstraction than space, making them more tangible to be integrated into different scientific approaches, as has been shown in archaeological research on proto-urbanisation (Ortman et al., 2020).

4. The material body of urbanisation

Urbanisation produces a material accumulation that occurs in a highly structured manner contained in archetypical material assemblages. The aim of what we call '*technomass*' is to provide a meaningful scientific continuous measurement of such assemblages. At the same time, archetypical material assemblages possess a set of structural properties such as 1) *particular shares of building materials* like glass, steel, concrete, plastics, and the like that can be identified for different locations and dates. These ratios can be easily obtained based on standard cubage calculations from engineering sciences or using general assumptions (Haberl et al., 2021; Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009); 2) the *energy profile* they imply, for cooling, heating and other forms of energy consumption and embodiment (Gros et al., 2014; Palme et al., 2018); 3) the *labour power* they contain (Ortman et al., 2020); 4) the *economic (monetary and non-monetary) value* they imply (Pettit et al., 2020); 5) a specific *material quality and complexity*; and 6) an *emerging urban morphology* that encompasses a rich phenomenological description of urban environments. We argue that these properties can establish meaningful connections with many scientific disciplines dealing with urbanisation and sustainability issues and can be linked to urbanisation impacts, like biodiversity loss, air pollution and greenhouse emissions and manifold outflows of wastes and emissions.

'*Technomass*' is an indicator that embodies such structural properties. It is conceptually and operationally different from other indicators that have been used in industrial ecology (Fig. 3), accounting for material stocks (Haberl et al., 2021; Kalt et al., 2021; Miatto et al., 2024). This analytical distinction between technomass and material stocks can be illustrated with the example of a building's demolition, which encompasses a phase change from a standing building (archetypical material assemblage) to a pile of demolished materials. Demolition entails a

Fig. 3. Demolition in Brussels.
Source: author's personal archive.

change in the particular way materials are assembled, while their amount remains essentially the same. However, a fundamental shift in the material properties takes place. For instance, a building as an archetypical material assemblage, embodies and communicates (matter that carries information) its own teleology, as a purposive designed object to fulfil a specific function, and it produces specific impacts accordingly. It possesses lower entropy and higher economic value, and is operationally expressed therefore using the material assemblage as a carrier of the unit of measurement, i.e. tons per hectare of technomass contained in buildings, roads, etc. (Inostroza, 2014). On the contrary, a material stock is a pile of materials without teleology (random), higher entropy and lower economic value. It is expressed in the weight or volume of single disaggregated materials, like plastic, concrete, iron, copper, etc. Therefore, a material assemblage is, by definition, different from a simple material stock. Meaningful definitions matter while addressing the DNA of urbanisation.

4.1. Urbanisation is a continuous spatiotemporal process

Contrary to a dichotomic approach such as urban-rural, a continuous measurement accounting for the differential degrees and intensities of urbanisation is the cornerstone to analysing and measuring its impacts (Inostroza et al., 2019). For instance, the concept of a suburban area – without conceptual agreement within the scientific community as to which this particular space is exactly meant by this term and thus a comparatively abstract construct – it does as such not provide any clue of the type of urbanisation patterns it contains. On the contrary, an urbanisation degree in the order of 10,000 ton*hectare^{-1} allow several scientific disciplines to understand and quantify a broad set of social and ecological impacts, such as UHI, carbon emissions, impact in water cycle and the like. However, urban science at large is still missing appropriate indicators to measure urbanisation on a continuous basis using continuous variables that reflect a measurable physical property of urbanisation. Advancing such indicators is crucial in developing a new science of cities.

4.2. Detectable material and social structural asymmetries through technomass differentials

The urban space is produced through socio-ecological processes, in particular urban conditions that are produced and reproduced by specific actors assuming particular roles in producing socio-ecological configurations (Heynen et al., 2006). Two overarching types of socio-ecological asymmetries can be mentioned: (1) asymmetries between social classes, with the encapsulation of those few appropriating and accumulating the benefits, such as better material conditions or access to green space; (2) asymmetries between urban tissues within the same city, where particular areas developing capsules of prosperity co-exist with areas falling into obsolescence and deterioration. Thus, it is replicating and deepening internal economic and socio-ecological asymmetries. Such asymmetries are usually higher within the same city than between different cities. In the distribution of benefits and impacts, asymmetries are more internal than external to urban areas. The materiality of urbanisation is one way to unveil such socio-ecological asymmetries.

4.3. Urbanisation is made of technomass

Urbanisation is a spatiotemporal process producing and reproducing a socio-biophysical transformation of space and leaves phenomenological traces in the form of material structures. Urbanisation unfolds in very specific material assemblages, purposive objects like buildings and infrastructures that are highly complex themselves at smaller scales. Such urbanisation traces can be measured by weight and/or volume (ton, m^3) per unit of space (m^2, hectare, km^2) and time (per minute, per day, per year). Technomass is a quantification of the materials that have been already accumulated and can be directly measured in an aggregated manner. A differentiation into different materials using standard knowledge from engineering is also possible (Inostroza, 2014). Technomass quantification includes only materials that have been transformed by human labour, being this a physical or chemical transformation that is always purposive, i.e. it does not include any excretions nor organic material that can be accounted as biomass or energy.

Technomass describes the continuous spatial structure of urbanisation (Inostroza et al., 2019) based on a physical property and not in arbitrary spatial or demographic assumptions. Continuous measurement of urbanisation can describe the broad scope of the spatiotemporal intensities of urbanisation in a comparable manner, from distant geographies and times (Figs. 4 and 5). The indicator offers a solid operational alternative to other existing indicators that rely on land use change or similar two-dimensional representations. In this way, urbanisation's materiality can be linked to manifold socio-ecological impacts. Consequently, by definition and without further assumptions, this indicator provides a continuous measurement of urbanisation based on a self-evident physical property that possesses a high comparative value. Technomass (Inostroza, 2014) allows a continuous, unambiguous and non-categorial measurement of urbanisation that is not biased by socioeconomic and geographical diversity (Fig. 5) and can be applied in any type of landscape and city.

4.3.1. In landscapes

The biophysical conditions of landscapes have been largely analysed (Wrbka et al., 2004). However, there is a disciplinary disconnection between studies that focus either on the natural or the built aspects that produce a dismissal of human-made infrastructures like buildings and infrastructures as components of landscapes (Inostroza et al., 2019). Even the smallest infrastructure in a remote area (Fig. 4) requires paramount amounts of technomass to be extracted, processed, transported and built, with manifold ecological effects that can be scientifically addressed by looking at this material dimension. However, technomass present in remote areas does not count as belonging to the urban space. Looking at urbanisation as a material accumulation process allows for a continuous measurement that is also closer to reality and thus more meaningful than aggregated, dichotomous categories. This approach enables the systematic accountability of manifold manifestations of urbanisation intensities, like differential infrastructures through landscapes, equipped natural areas, farms, (Fig. 4) small and large cities (Fig. 5). Indeed, the construction materials' global demand has grown exponentially since the 1950s to be transformed into buildings and technological infrastructure that will remain stocked in landscapes for centuries (Krausmann et al., 2009; Steinberger et al., 2010; Wiedenhofer et al., 2015). It is necessary to use novel indicators (Fig. 4), to make them visible for landscape science and related disciplines.

Technomass and biomass in the form of built structures and natural elements are highly intertwined at several spatial scales. It produces a high material and social complexity of urbanisation that can be disclosed by using technomass to unveil manifold material effects (Inostroza, 2018).

Fig. 4. Full spectrum of urbanisation degrees found in southern Patagonia. Source: own elaboration, unpublished.

4.3.2. In urban cores

The high spatial, material, morphological and social complexity of urbanisation occurs at very short distances in four dimensions. The capacity to capture the city in three physical dimensions has been greatly enhanced by recent developments in remote sensing (e.g. Frantz et al., 2020; Geiß et al., 2019; Li et al., 2020). However, the temporal aspect of 3D urban change remains mostly neglected due to data issues, and thus plays a subordinate role and must be given more attention (Wentz et al., 2018). The 'Technomass' makes it possible to measure different landscapes with their material assemblages in a single unit – from 1 to 10 tons per hectare in remote areas up to more than 1,000,000 tons per hectare in Central Business district urban cores (Fig. 5). This allows the DNA of the location to be decoded and measured consistently and uniformly.

4.4. Limitations

We have analysed urbanisation as a phenomenological material transformation of space, that allows humans to perform urban activities. DNA is a material structure, a molecule, that allows life its reproduction. We used the DNA as a metaphor to express that, anthropogenic materials, i.e. technomass, provide the necessary conditions for the reproduction of urban space and the continuity of all its functions. Therefore, the material conditions are determining the reproduction capacity of urban space.

We acknowledge that urban space is highly complex and multidimensional including manifold idiosyncratic manifestations that produce the great urban diversity that we observe in cities across the world. While technomass can provide a robust continuous description of the urbanisation process, it cannot certainly encompass all angles of its complexity. Therefore, such material description might be complemented with other socio-cultural dimensions that concern other disciplines interested in urbanisation.

5. Conclusion

Addressing the high complexity of the urbanisation process in the XXI century requires conceptually and analytically different approaches than in the past. Urbanisation has been understood mostly as a

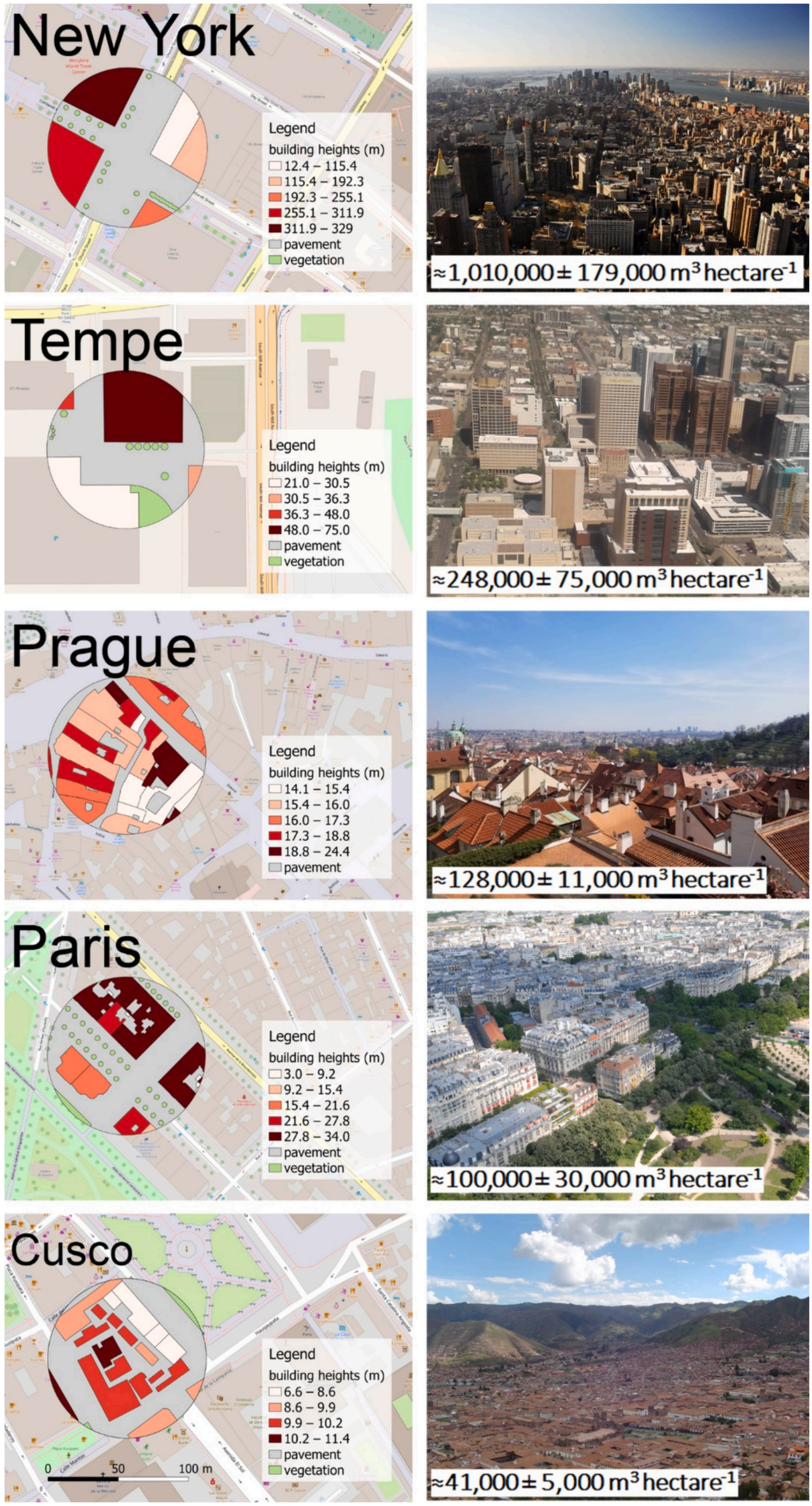

Fig. 5. Amounts of technomass found in 5 different cities around the world.
Source: own elaboration over Google Maps ©, Google Earth Pro © and own datasets from previous research, unpublished.

demographic and categorical phenomenon. In this essay, we have proposed an understanding of urbanisation as a continuous spatiotemporal process, without dichotomies and categorical concepts by using indicators that are based on a physical and continuous unit of measurement. We propose technomass, an indicator that measures the amounts of anthropogenic materials accumulated in space as a phenomenological continuous expression of the urbanisation process. Our approach is both, data-driven and spatially explicit, not requiring any further assumptions and allowing a strong continuous representation of the complex heterogeneity and the observed spatial patterns at several scales. On this basis, the differential impacts of urbanisation can be linked across the globe, it can be spatialized and compared across distant places and time, looking for instance, to the impacts of UHI and technomass, or ecosystem services and technomass. Technomass is a process-based conceptualization where the fluxes of materials from source to sink can be analysed and measured linking urbanisation and sustainability. The strength of technomass measurement relies on its comparability, continuity, and independency of settlement morphologies. However, communications and networks are not always proportional to the technomass and are thus expressed in the form of flows rather than technomass which is a measure of stocks.

A robust operational framework to analyse, measure and ascertain urbanisation can be constructed using the process of material accumulation over time—history in a broader sense—depending permanently on pre-existing ecological attributes—i.e., natural capital—located either in the hinterlands or even in faraway locations. Material accumulation is at the vortex of the urban organisation, producing the very urban material structure allowing its reproduction. Rather than space, which is ubiquitous and highly abstract, it is anthropogenic matter what makes urbanisation possible, observable and qualitatively idiosyncratic. It is an approach that unveils the underlying thermodynamics implicit in urbanisation processes.

Technomass reveals urbanisation's DNA, as unfolding in a continuous manner that follows regular, teleological and archetypical material assemblages that transcend geographies and time. The presence of technomass reveals urbanisation's DNA indicating the presence of humans, now, or in the past. Exactly like in the case of DNA, that indicates the current or past presence of an organism (Taberlet et al., 2018). This materiality is objective and can be directly measured and compared providing a solid ground for a theory of urbanisation encompassing even the origins of cities as such. On the practical level, it can foster comparative international research on urban margins, new suburbs, that are no longer concentrated around cores but spread across increasingly vast urban regions shedding light on qualitative imbalances between the centre and the periphery. At the same time, it can open new perspectives on spatial planning implications, the obsolescence of administrative boundaries, and the reinforcement of spatial planning for large areas or urban regions, whose dynamics and new resulting boundaries can be better addressed using technomass and material flow analyses. A continuous measurement of urbanisation, i.e., a measurement based on a clear, physical measure, as we have proposed in this essay, makes evident the direct and indirect socioecological effects of urbanisation, over the basis of robust, comparable and reproducible empirical evidence. Such an indicator can bring together different research communities in integrative approaches aimed at addressing the elusive sustainable urban development. This is an operational conceptualisation that places the process of material accumulation as the urbanisation's DNA.

CRediT authorship contribution statement

Luis Inostroza: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hannes Taubenböck:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

Luis Inostroza reports article publishing charges and travel were provided by Mendel University in Brno. Luis Inostroza reports a relationship with Mendel University in Brno that includes: employment and travel reimbursement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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