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Advancing urban metabolism studies through GIS data: resource flows, open space networks, and vulnerable communities in Mexico City.

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Abstract: Urban metabolism studies provide valuable insights that can improve resource efficiency at the city scale. However, only a limited number of such studies include spatially explicit data to inform planning practitioners. In this article, we argue that integrating spatially explicit urban metabolism data in urban planning can leverage resource-efficient development and management of open space networks. Based on this premise, our research presents a methodological strategy to investigate how the use of GIS data can improve the

applicability of metabolic studies in urban planning and the management of open space networks in particular. GIS-based urban metabolism assessment of Mexico City was performed at the city scale, including data on vulnerable communities, communal lands, and indigenous areas. After mapping selected GIS layers, a detailed resource-efficiency analysis was performed through the compilation of a Borough Pattern Scan, based on quantification of resource use, total areas of resource infrastructure and public open spaces. The results of our multi-scale spatially explicit analysis provide an improved understanding of borough metabolic profiles which can leverage a more resource-efficient development of open space networks in Mexico City.

1. INTRODUCTION

1.1 URBAN METABOLISM AND OPEN SPACE NETWORKS

Growing evidence demonstrates that cities with high resource consumption and waste generation are more vulnerable to scenarios of future resource scarcity due to climate change and global population growth (Manna et al., 2018; Parish et al., 2012; Hanjra & Ejaz Qureshi, 2010). Urban planning defines urban forms and the types of infrastructure in a city depending on geographic characteristics and construction material preferences, thus determining an important part of the overall resource efficiency of the urban fabric (Yang et al., 2014; Pincetl et al., 2012; Deilmann, 2009). Urban Metabolism (UM) research has evolved substantially in recent years by adopting an interdisciplinary and multi-scale approach in the analysis of internal resources and social-ecological dynamics in urban systems, encompassing different lines of thinking as in industrial ecology, urban ecology, political ecology, and political-industrial ecology (Newell et al., 2017; Newell and Cousins, 2015; Castán Broto et al., 2012). In industrial ecology, UM is defined as the sum total of all technical and socio-economic processes associated with the production, distribution and consumption of resources that occur in cities, resulting in growth, production of energy, and elimination of waste (Kennedy et al., 2007). UM studies provide valuable insights to inform strategies for more resource-efficient cities by developing holistic frameworks for urban modelling (Kennedy et al., 2011; Barles, 2010), which can advance understanding of the impacts of human activities on the natural environment.

In this article, we argue that integrating spatially explicit UM data into urban planning can leverage the resource-efficient development and management of open space networks (OSN).

OSN are interconnected systems of natural and semi-natural green-blue infrastructure areas and public space in an urban region (Frazier & Bagchi-Sen, 2015; Linehan et al., 1995). From a UM perspective, planning strategies of OSN can help generate or recycle resources as well as reduce demand for them through an optimized, multi-scalar, and qualitative use of urban space (Kennedy et al., 2011; Agudelo-Vera et al., 2012; Leduc and Van Kann, 2013). In other words, OSN can be used as an asset to minimize resource extraction, energy consumption and waste generation, while preserving urban ecological dynamics.

Previous spatially explicit UM studies have illustrated spatiotemporal dynamics of materials and resource flows and infrastructure at multiple scales (Yeow & Cheah, 2019; Smit et al., 2019; Spierre Clark & Chester, 2017, Guibrunet et al., 2016), building stocks (He et al., 2020; Mao et al. 2020; Lanau & Liu 2020; Miatto et al., 2019), energy and water urban harvesting scenarios (Agudelo-Vera et al., 2012), and integrated the spatial dimension of environmental and socio-economic information (Caputo et al., 2019; Choe & Thorne, 2019; Farzinmoghadan et al., 2019; Juwet & Ryckewaert, 2018; González et al., 2014; Leduc & Van Kahn, 2013). However, these studies mainly focused on the quantification of resource flows/stocks, their circulation and location in urban systems, and the relations of power among stakeholders, without considering the use of space as a means to improve the resource efficiency of the system being studied. A growing number of works highlight the benefits of integrating spatially explicit accounts of UM flows/stocks for informing policy-making and resource management strategies at the city level. For example, mapping the distribution of energy demand by district in Bengaluru, India, allowed Nalini (2016) to understand the local water-energy nexus and the spatial dimension of UM flows and resource infrastructure. By overlapping spatially explicit water and energy datasets, researchers were able to relate the location of inefficient sections of the drinking water distribution network and pumping facilities with high energy consumption districts and geographic features of the city. Wielemaker et al. (2019) used geographic boundaries, socio-demographic data, and GIS-based information on urine and feces at the neighborhood and building levels in Amsterdam to produce a spatially explicit inventory of nutrient hotspots in several areas of the city. The spatially explicit data at the local level allowed to identify clusters of buildings with a high nutrient load and, through this, to better inform the planning of future sanitary systems. These studies demonstrate the value of spatially explicit UM data on critical flows/stocks (energy, construction materials and nutrients) at different scales (regional, urban and building) and suggest further research to consolidate spatially explicit data harvesting methods. However, they did not focus on applicability of results in practice or the identification of opportunities to enhance the incorporation of UM results into urban planning and design strategies (Perrotti, 2019). Consideration of urban spatial structures (i.e., open spaces) underpinning metabolic flow/stock dynamics can favor the uptake of UM studies by planning practitioners and, consequently, significantly contribute to the development of a systemic approach to resource efficiency in urban systems (Perrotti, 2020).

Reinforcing and preserving existing OSN in urban areas can increase urban populations' exposure to natural environments, enhance biodiversity, increase soil water infiltration and reduce the concentrations of atmospheric pollutants (Tratalos et al., 2007; Cohen et al., 2014), while providing opportunities for recreation and physical activity, promoting community identity and a sense of well-being (Perrotti & Iuorio, 2019), and increasing economic benefits (Zhang et al., 2012), among other social-ecological benefits (Perrotti et al., 2020). Previous research on OSN has, for example, focused on land-use regulations to preserve existing ecological networks (Ahern, 2004; Weber & Wold, 2000), applied landscape ecology models to integrate future vacant lots in shrinking cities (Frazier & Bagchi-Sen, 2015), investigated energy and resource requirements for scaling-up urban agriculture (Mohareb et al., 2017), and designed scenarios to reframe circular economy questions through urban and landscape planning strategies (Amenta & Van Timmeren, 2018; Marin & De Meulder, 2018). Another prolific line of research focused on assessing the loss of connectivity among fragmented green patches caused by uncontrolled urban form and urban sprawl (Yacamán Ochoa et al., 2020; Toger et al., 2016). It demonstrated that enhancing connectivity can provide higher social-ecological values in urban environments (Frazier & Bagchi-Sen, 2015).

Despite the increased focus on the social-ecological values of OSN over the last decades, only a limited number of studies have related the spatial configuration of open spaces with resource accessibility; this represents a critical frontier in UM research. Spatially explicit studies on resource consumption and the availability and accessibility of utility networks and infrastructure can help urban and landscape planners identify opportunities in the urban space for mitigating resource-related vulnerabilities (e.g., neighborhoods with high energy demand and/or significant solid waste generation) and enhancing the harvesting of local resources through spatial design strategies. Based on this premise, this article will present a methodological strategy to investigate how the use of GIS-explicit data can improve the applicability of UM studies in the planning and management of OSN. Addressing this question can provide novel insights into using OSN to achieve more efficient distribution and concentration of UM flows and infrastructure in urban systems.

1.2 BACKGROUND: MEXICO CITY

Geography, vulnerability and governance

Mexico City is located on a plateau at 2,400 meters above sea level, surrounded by volcanic mountains in the Valley of Mexico with a total area of 1,480 km^2 and approximately 8.9 million inhabitants. An estimated 3.4 million live below the poverty line with a condition of social and economic vulnerability (CONEVAL, 2018; Aguilar & Mateos, 2011). These vulnerable communities are located in low-income neighborhoods on the urban-rural periphery and in deteriorated areas of the city center and have deficiencies in terms of access to education, healthcare, basic services, public space, housing quality conditions, and property titling (Ziccardi, 2016; Bayon & Saraví, 2013; Aguilar & Mateos, 2011). The large urbanized region within which Mexico City is located is known as the Metropolitan Zone of the Mexico Valley and has a total population of approximately 21 million, including 60 other municipalities in the states of Hidalgo and Mexico (see Figure 1). Mexico City is managed by a city government (*Gobierno de la Ciudad de México*) and includes 16 independent boroughs (*alcaldías*) with diverse geographic and socio-economic characteristics. The boroughs are subdivided into neighborhoods (*colonias*); for statistical analysis, these are divided into rural and urban "basic geostatistical areas" (AGEB, *Área Geo-Estadística Básica*), which constitute the smallest units of the national census.

(Insert Figure 1 about here)

Approximately 59% of Mexico City's land area is classified as Conservation Land (*Suelo de Conservación*) due to unique climatic, topographic, and soil characteristics, and includes a variety of agricultural and natural ecosystems such as forests, grasslands and wetlands. About 12% of the Conservation Land is urbanized (SEDEMA, 2016) and 3% is covered by informal settlements (*asentamientos humanos irregulares*), i.e., vulnerable communities in which the inhabitants do not have legal ownership of the land and basic services are limited due to the irregular legal land occupation, precariousness of dwelling construction, and risk of eviction for being located in hazardous areas of high ecological value (Aguilar and López Guerrero, 2012; UN-HABITAT, 2003). Moreover, being built without the support of local authorities, they are not always connected to the municipal utility networks and, in some cases, basic needs (e.g., drinking water) are fulfilled through informal means such as water trucks, public hydrants, natural springs, rivers, and wells (Aguilar and López Guerrero, 2012). However, these areas can play a key role in future natural-system conservation strategies and the management and planning of new infrastructure and OSN (Wigle, 2010), since they are located at the intersection of the urban environment, natural reserves, communal lands, and indigenous areas (*pueblos originarios*).

Communal lands are properties given to farmers after the Mexican Revolution (1910–1912), and are held by a community for agriculture use, residential settlement, and public use. This period of land reform ended in 1992, with a constitutional amendment that allowed privatization of communal lands (Lerner et al., 2018; Jones & Ward, 1998) and resulted in the conversion of green areas into new urban developments. Due to rapid urban growth over the last 30 years, communal lands were annexed to areas inhabited by indigenous, which were originally rural areas that historically developed independently from Mexico City (Arach et al., 2018; Medina, 2009). These indigenous areas, are territorial units, which preserve and reproduce totally or partially their own social, economic, cultural and political institutions, establishing their political status with juridical personality, their own patrimony and right to self-determination (SEPI, 2019). All indigenous areas have leaders elected by their community, who have the responsibility to encourage collective works for common benefits, organize community work and social development projects, and establish agreements between neighbors to solve conflicts such as those associated with the distribution of resources and common lands (Ortega Olivares, 2010). Communal lands and indigenous areas are relevant to our research, as they have in common the legal and spatial capacity (i.e. independent governance supported by local authorities and areas with public open spaces) to organize different communities with a local-scale and community-led approach toward decentralized resource management, to preserve their cultural heritage, identity and habitat.

Existing UM studies

The use of a UM approach to study Mexico City is still limited to few research projects. Depending on the discipline and focus of the study, these vary with regard to the metabolic flows analyzed and scale of study (Delgado-Ramos, 2021, 2015a, 2015b, 2013; Huerta-Barrientos, 2018; Guibrunet et al., 2016; Kennedy et al., 2015; Hoornweg et al., 2011; Paez, 2010). However, the translation of these studies into spatially explicit accounts (e.g., GIS mapping) of resource flows/stocks and an understanding of the role of OSN in resource management in Mexico City are still limited to date. Researchers have used UM frameworks to study the configuration of waste management systems, drinking water consumption and water infrastructure (distribution system and sewer network) from an urban political ecology perspective (Guibrunet et al., 2016; Delgado-Ramos, 2015a). Other studies have focused on the impact of material flows on GHG emissions (Delgado-Ramos, 2015b; Hoornweg et al., 2011) and the assessment of a social-ecological metabolism (Huerta-Barrientos, 2018), included Mexico City in a comparative study of 27 megacities worldwide (Kennedy et al., 2015), and examined the potential benefits of urban energy transition (Paez, 2010). Guibrunet et al. (2016) studied the role of the informal sector in the collection and recycling of municipal solid waste (MSW) in areas of Mexico City where municipal waste collection services are not available. They focused on urban waste flows in the Tepito neighborhood (*Cuauhtémoc* borough), where, following the development of a parallel political structure by local leaders (*caciques*), basic services were provided in exchange for an informal tax paid to the local community. MSW flows were mapped to understand the available distribution and disposal infrastructures, to compare the public, private, and informal waste management systems, and study their interdependence. However, the approach proposed by Guibrunet et al. did not encompass a spatially explicit accounting of MSW flows (e.g., GIS map with solid waste generation by borough or AGEB). Delgado-Ramos (2015a) described the environmental and economic challenges arising from the development of the drinking water distribution system. In particular, he studied the inflow of bottled water (the most common solution for consuming drinking water in Mexico City), inequalities in the distribution and access to drinking water across high/low-income boroughs (which can have a difference of 3 to 1 in total per capita consumption), as well as the social movements for environmental justice related to water accessibility.

In conclusion, based on the results of our preliminary context analysis and previous UM studies, Mexico City provides a relevant case study for our research due to: i) its complex and energy-intensity infrastructure for water extraction, distribution and drainage, ii) a large population living in informal settlements and low-income neighborhoods that are more vulnerable to access basic services and public space; iii) the high concentration of common lands, indigenous areas, resource infrastructure, and nature reserves in several areas of the city.

2. MATERIAL AND METHODS

We performed a Geographic Information System (GIS)-based assessment of the metabolism of Mexico City at two urban scales: city administrative boundary (including the 16 boroughs) and borough scale. These scales were investigated through the compilation of primary GIS data (see supporting information) and the following available datasets: (1) resource flows, including drinking water consumption and wastewater outflows, electricity consumption, generation of organic and inorganic MSW, and construction solid waste (CSW); (2) location and capacity of utility infrastructure and resource management facilities; (3) geographic features of the city (e.g., topography and land-use cover areas), including OSN; (4) location of informal settlements and socio-demographic characteristics; and (5) location of indigenous areas and communal lands and their administrative limits.

Resource infrastructure datasets include main generation, distribution, and storage facilities within the city administrative boundary (electrical power plants and substations, water distribution system and sewage network, recycling and compost plants). OSN datasets include public and private green spaces (parks and gardens), blue spaces (rivers, streams, channels, and lakes), gray spaces (squares and pedestrian walkways), and nature reserves.

Vulnerable communities' datasets include location data for informal settlements and areas with a high urban marginality index. The high urban marginality index was presented in the Mexico City Resilience Strategy report (CDMX Resilience Office, 2016); we used it to assess the overall degree of deprivation for the population in each AGEB based on a set of socio-economic variables. These include percentage of children without access to education, population without access to health services and high death rate at birth, as well as population living in houses with dirt floors and not connected to the water and sewage system.

Borough Pattern Scan

After mapping the selected GIS layers, a detailed analysis of per capita data patterns was performed for each borough. The boroughs were classified according to their (high/low) resource efficiency. We intentionally use a broader definition of resource efficiency, which is intended to be an optimal combination of low resource use (UM flows) and high resource access (resource infrastructure and OSN). Boroughs were classified as more resource efficient if they had lower resource use (less resource consumption and waste generation than the city average) and higher resource access than the city average; inversely, boroughs with higher resource use and lower resource access were classified as less resource efficient (see Figure 2).

(Insert Figure 2 about here)

The criterion used to analyze resource use was the total amount of resource consumption (for water and energy flows) or generation (for solid waste flows). For resource access, the criteria used were the location and capacity of resource infrastructure by type of flow, and the location of OSN. Each criterion is characterized by sub-criteria (see supporting information), which were defined using spatially explicit data. The Borough Pattern Scan allowed for the identification and classification of areas with high or low resource efficiency based on resource consumption/infrastructure and urban space availability (i.e., OSN). Spatially explicit socio-economic datasets were used to characterize resource efficiency by identifying communities affected by resource vulnerability (informal settlements and areas with high urban marginality index), and decentralized resource management structures (communal lands and indigenous areas).

To classify the boroughs, each sub-criterion was evaluated using a value index (see supporting information for details on calculations). A “1” score was assigned to the highest value of each sub-criterion and a “0” score in case of a null value. Then, the scores for the remaining sub-criteria were proportionally calculated based on comparison with the highest score. For example, *Cuauhtémoc* had the highest quantity of MSW generation per capita and was evaluated with a score of 1; *Iztapalapa* had half as much MSW generation per capita and was evaluated with a score of 0.5. The final score of each criterion corresponds to the mean of all scores assigned to its sub-criteria (e.g., the values assigned to solid waste flows of all boroughs were calculated as mean values of the sub-criteria MSW and CSW generation). Finally, to highlight high/low scores for each criterion, criteria with scores above the mean score were marked with a “+” symbol and those under the mean score with a “-” symbol.

3. RESULTS

Table 1 illustrates the quantification and classification of all data used in the GIS analysis by criteria and for each of the 16 boroughs; sub-criteria with values 10% above the average are highlighted in red, while orange is used for average values, and gray for values 10% below the average. All values are on a unit-per-capita basis, except for the vulnerable communities, communal lands, and indigenous areas criteria, in which values are provided based on total square kilometers by borough.

(Insert Table 1 about here)

The first set of maps refers to the spatial distribution of resource flows and utility infrastructure by borough (Figures 3, 4, and 5), including total and per capita resource use, and the location of resource infrastructure, administrative/storage facilities, and main distribution network. The second set of maps includes the distribution of OSN (Figure 6.a), and the location of areas characterized by vulnerable communities, communal lands, and indigenous areas (Figure 6.b). Results of the Borough Pattern Scan are presented in Figure 7, including a set of tables (Figure 7.a) and a synthesis map (Figure 7.b), in which the spatial distribution of resource infrastructure, OSN, and vulnerable communities within communal lands and indigenous areas are overlaid to highlight hotspots of in-boundary spatial relation dynamics (e.g., location, elevation, overlapping, type of boundaries, closeness). The synthesis map allows for identification of the OSN or their components; it can be used to mitigate context-specific resource-related vulnerabilities and enhance resource-efficient urban and landscape planning strategies.

Resource use

The result of our mapping highlights that boroughs in the city center (*Azcapotzalco*, *Benito Juárez*, *Cuauhtémoc*, *Miguel Hidalgo,* and *Venustiano Carranza*) have the highest resource use per capita compared to the per capita average for Mexico City as a whole. The lowest resource use is concentrated in two areas of the city: the northeastern boroughs with vulnerable communities (*Gustavo A. Madero*, *Iztacalco* and *Iztapalapa*) and the southern rural boroughs with the highest surfaces of informal settlements (*Milpa Alta*, *Tlalpan*, *Tláhuac* and *Xochimilco*). In Mexico City, average water consumption is 350 l/day/capita, and electricity consumption is 1,753 kWh/year/capita. Five out of the 16 boroughs generate more municipal solid waste per capita than the average (1.42 kg/day), of which all except *Xochimilco*, are located in the city center and encompass more than 50% of the illegal dumping sites.

Resource infrastructure

Southern boroughs with rural areas are best equipped with water supply infrastructure compared to all other boroughs, while northern boroughs concentrate most solid waste infrastructure in the city and a borough in the city center has the most energy infrastructure. Even though almost every borough has a MSW transfer station, the average pickup radius distance to the transfer station is between 5 km and 12 km, which increases transport distance and, therefore, the associated fossil fuel consumption. Southern rural areas are crossed by 90 km of the Cutzamala-Lerma aqueduct and the electrical power main distribution system. Almost 50% of all rural areas are not equipped with any MSW treatment facility, and the only compost plant in the city is located in the northern urban area of *Venustiano Carranza*, more than 30 km away from the agricultural areas.

In *Iztapalapa*, the Cerro La Estrella natural reserve areas concentrate 50% of all informal settlements. These areas are less than 9 km away from the Bordo Poniente compost plant and 4 km away from the Central de Abastos food-supply complex, which encompasses the two MSW treatment plants. *Gustavo A. Madero* contains the highest number of MSW facilities (including the only recycling plant in the city). The recycling plant is located at the eastern side of the borough and centralizes all such facilities, increasing the distance for transportation of MSW from other areas. The location and proximity of vulnerable communities to the MSW infrastructure and OSN is similar in the two boroughs. As we will see in the Discussion, this points to a potential use of existing open spaces to enhance resource harvesting while improving its accessibility.

Open space networks

The OSN map (Figure 6.a) shows the existing typologies of open spaces and highlights how urban areas contain almost 90% of all the public green-gray spaces. In comparison, rural areas contain more than 92% of the natural reserves, agricultural fields, and blue spaces. Results show that the average quantity of green-gray-blue open spaces available in Mexico City is 3.14 m^2/inhab. This is significantly lower than in other cities with similar population density, as for example Madrid, Spain, where it reaches 14 m^2/inhab. (ADB-IDB, 2014). The highest quantities of public green spaces per capita in urban areas are found in central boroughs that concentrate low amounts of land areas with high urban marginality indices and informal settlements, such as *Miguel Hidalgo* and *Coyoacán*, where they reach 14 m^2/inhab. and 7 m^2/inhab., respectively. Three of the five boroughs with the lowest amount of public green spaces (less than 1m2/inhab.), *Iztapalapa*, *Gustavo A. Madero*, and *Xochimilco*, concentrate 38% of the total population of Mexico City and the highest number of land areas that concentrate informal settlements and high urban marginality indices (44 km2 and 30 km2 respectively), revealing the inequalities in the distribution of OSN between vulnerable communities and other neighborhoods. *Milpa Alta* has the largest land area, with 269 km^2, the lowest population (137,000 inhabitants), and the lowest electricity consumption (371 kWh/year/capita) in the city. Natural reserves extend over three quarters of the borough's total land area, and the only waste-to-energy plant is located in the northern zone, more than 20 km away from the southern agriculture areas.

(Insert Figure 3 about here)

(Insert Figure 4 about here)

(Insert Figure 5 about here)

(Insert Figure 6 about here)

(Insert Figure 7 about here)

4. DISCUSSION

OSN as a medium to increase resource efficiency

The table and maps presented in the Results section highlight the location and proximity of areas in which urban flows and infrastructure are concentrated, both at the city and the borough scale. Our aim is to present a methodological strategy to investigate how spatially explicit information and data on resource use, resource infrastructure, and OSN can improve the applicability of UM assessments in the planning and management of green-blue-gray public spaces. We focused on OSN as a medium to increase resource efficiency while considering the specific socio-economic conditions of vulnerable communities as well as the assets of the local natural capital.

While Mexico City counts 67 m^2 of public green areas per inhabitant, these areas are not equally distributed across all parts of the city; they can vary depending on the type of spaces included (e.g., squares, parks, nature reserves) or type of calculation (e.g., based on ground cover or tree coverage) as shown in previous research (PAOT, 2018; Maldonado-Bernabé, 2019). In rural areas, our results show that the available public green area is limited to 3.44 m^2/inhab.; this does not include natural reserves within the Conservation Land, which are not considered to be accessible (lack of pathways and benches for elderly and disabled people), nor safe (lack of illumination increasing the feeling of insecurity), nor functional (lack of facilities such as public toilets) to all inhabitants (WHO, 2010). Previous research demonstrated that the distribution of public green areas per inhabitant in Mexico City is directly related to each borough's socio-economic characteristics, with lower quantities of green areas in lower-income neighborhoods (Fernandez-Alvarez, 2017; Checa Artasu, 2016). We identified seven boroughs that have lower quantities of public green areas (less than 9 m^2/inhab.), including four boroughs with high resource use: *Azcapotzalco*, *Benito Juárez*, *Cuauhtémoc*, and *Venustiano Carranza*. Future plans to increase available green space in these boroughs could provide opportunities for integrating new utility infrastructure (e.g. public retention basin parks) to improve resource access and enhance the transition from a linear to a circular metabolism.

Xochimilco has the second-highest MSW generation rate in the city (2.24 kg/day/capita) and is a high-density, rural, low-income indigenous community. The borough could benefit from its productive agricultural land to reinforce the existing local composting systems, create new organic waste treatment plants, produce energy from waste (e.g., composting, anaerobic digestion), increase energy access for the local population, and provide compost and digestate for future agriculture production. Synergies among different urban functions could lead to mutual benefit in terms of resource cycling, especially for fertilizers and energy production (Wielemaker et al., 2018). Previous research in other contexts studied the energy potential from composting and incinerating all organic MSW; for example, in Denmark, this would be equivalent to 5% of the country's total energy consumption, including transport (Lehmann, 2011). The use of under- or unused surfaces in and around infrastructure facilities could be used to install renewable energy systems (e.g., photovoltaic panels). Previous studies suggest that, depending on the total amount of available area and local climatic characteristics, this energy could be used for private or public transport (Neumann et al., 2012), reducing fossil fuel consumption and associated GHG emissions while promoting the use of underexploited surfaces in the city to produce energy (among other benefits).

Decentralized and multifunctional planning of OSN

A long-term overexploitation of the city's underground aquifers and its complex drainage system has resulted in the depletion of the aquifers, causing shortages in the water supply system and subsidence in some areas of the city (Legorreta, 2006). To meet 42% of total urban water demand (SACMEX, 2018), the Cutzamala-Lerma system, an energy-intensive and expensive drinking water system (Tortajada, 2006), pumps water to Mexico City from rivers more than 1,000 km away. About 2.280 million kWh are required to pump all this water, equivalent to the total electricity consumption of the 6.5 million inhabitants of the neighboring city of Puebla (SACMEX, 2012).

Building on the assessment of resource use and available areas of OSN at the borough scale as summarized in the Borough Pattern Scan, planning strategies can be proposed to increase the accessibility and efficient use of these resources. Highly urbanized boroughs with high drinking water consumption per capita (e.g. can expand their water supply system by adding decentralized infrastructures. Since 2019, the Mexico City SCALL (*Sistema de Captación de Aguas de Lluvias*) program has developed rainwater harvesting (RWH) solutions for individual homes in boroughs with water accessibility issues. Although the number of beneficiaries increases every year, a considerable part of the city's vulnerable population is unable to benefit from the program, due to a lack of required official documentation such as residence certificates and planning permits (SEDEMA, 2019). Planning communal RWH systems in public spaces and in available, underused resource facilities (e.g., roofs and parking lots of water/electricity plants) can contribute to mutualizing efforts, reducing material costs, improving water accessibility for vulnerable communities, and reducing pressure on the current energy-intensive drinking water system through local and decentralized solutions (Valdez et al., 2016; Agudelo-Vera et al., 2012). Boroughs with high water consumption, in which utility infrastructures are mostly located in agricultural areas (e.g., *Milpa Alta*), could benefit from state-of-the-art design solutions for linear water catchment parks (Ibrahim et al., 2020). These could be constructed alongside existing aqueducts or below electric lines for use in agriculture irrigation, which could create an alternative or supplementary irrigation system and increase water storage capacity through wetland planning and landscaping. Moreover, the planning of a mixed RWH system on rooftops and publicly open green infrastructure could increase water accessibility for households not connected to the primary water drinking system while contributing to improving the connectivity of the whole OSN. As demonstrated in previous research, RWH systems can reduce household water and energy consumption as well as the overexploitation of groundwater consumption by providing an alternative water source, while preventing flooding by reducing stormwater flows in the rainy season (Jalife Acosta et al., 2018; Valdez et al., 2016; Nanninga et al. 2012; Legorreta, 2006).

Previous studies have demonstrated that informal settlements, along with other public and private infrastructure (e.g. highways and housing developments), contribute to the erosion of green areas in boroughs within the Conservation Land due to housing shortage and limited land accessibility (Aguilar & Santos, 2010). GIS mapping and spatial calculation are affecting the social organization, environmental impact, and regulation of informal settlements in the Conservation Land (Connolly & Wigle, 2017). Southern boroughs could reinforce existing territorial development plans driven by local authorities (e.g. *Tlalpan, Xochimilco*), integrating individuals and organized groups within the communities involved, to preserve and enhance local resources (e.g., forests, grasslands, and agriculture fields). Moreover, involving community leaders in participatory design processes and GIS data collection to create and manage new buffer areas of collective green spaces and resource infrastructure, would strengthen local socio-environmental organizations and favor the decentralization of resource management (Santos et al., 2015; Silva, 2013), while enhancing the individual land use and titling regulation processes.

OSN and the multi-scale UM approach

The selection of system boundaries and resource datasets used in UM studies depend on the research objectives and the level of disaggregation of available data at different urban scales (e.g., region, borough, street, building). The use of available fine-grain data at infra-city (borough) scale allowed identifying specific areas with disadvantaged socio-economic characteristics at the AGEB level, which favored a more detailed multi-scale approach. However, limiting our study to Mexico City excluded the possibility of studying the spatial relationship between resource use and infrastructure within the entire urban system of the Metropolitan Zone of the Valley of Mexico, which is home to a growing population vulnerable to OSN availability and resource accessibility (OECD, 2015). In addition, the fact that we focused our analysis on per capita values at the borough scale (i.e. Borough Pattern Scan), made it difficult to disaggregate the values into areas of interest based on the socio-economic characteristics of the population and the type of open space diversity of each borough (e.g. hotspot classification identifying different levels of vulnerability at a finer scale of a borough). Another limitation linked to the scale of analysis was the impossibility to collect data on informal resource flows (e.g. solid waste collection and recycling by organized groups in the communities) and to conduct field visits to vulnerable communities to understand their resource management relationships, which would have helped to better detail and localize the strategies proposed above.

The use of the Borough Pattern Scan allowed us to classify spatially explicit data by resource type; through this, we were able to study their location, overlapping, and proximity in relation to the geographic and socioeconomic characteristics of Mexico City. For the OSN datasets, information about land ownership was essential to pursue our research objectives based on publicly owned OSN. However, it is worth noting that the quantities of per capita private green areas (8.69 m^2) is almost triple that of public green areas (2.84 m^2 per capita). The Borough Pattern Scan could be calculated using different boundaries (e.g., AGEB, water catchments) in a specific urban area, adapting it to specific resource flows, its infrastructure, and internal diversity of OSN.

5. CONCLUSIONS AND FURTHER RESEARCH

Our research has provided a spatially explicit account of UM flows and infrastructure in Mexico City, integrating the mapping and assessment of OSN, and supported by datasets on vulnerable communities, communal lands, and indigenous areas. By presenting the Borough Pattern Scan and the spatialization of UM data on maps, we identified opportunities to increase resource efficiency by using OSN and their spatial configuration as a lever to sustainable urban and landscape planning. This research also contributed to a deeper understanding of the location and proximity of resource infrastructure and pointed to development opportunities for vulnerable communities in Mexico City. As shown in a previous study of the MSW system of Mexico City (Guibrunet et al. 2016), informal social organizations and alternative land/resource governance systems can engage different actors in the process of producing or transforming resource flows/stocks. The integration of socio-economic data in the UM study allowed us to identify spatial relations (and co-existence) between vulnerable communities, indigenous areas, and communal lands, which can enhance more resource-efficient urban and landscape planning strategies to mitigate vulnerabilities to resource access and enhance resource efficiency.

Despite limited access to spatially explicit datasets for Mexico City, we were able to compile spatially explicit UM datasets intended for use by planners and practitioners in planning and of OSN. This was possible by performing an integrated quantitative and qualitative spatial UM analysis based on classification of available GIS datasets as well as the plotting of existing quantitative data on maps. Then, through the use of Borough Pattern Scan, we could classify the type of spatial data needed to understand the dynamics of resource use and resource access and introduced the planning of OSN as a new strategy to leverage resource efficiency.

Based on the outcomes of our work, further research can focus on using finer-scale analysis for integrated UM and GIS analysis as a way to improve UM application in urban and landscape planning across different contexts. Such analyses can refine research results and provide a context- and community-specific understanding of metabolic dynamics, resource accessibility, resource governance and management, and planning strategies for nature conservation. Spatially explicit data on informal resource extraction, distribution and consumption (e.g., illegal water wells) should be systematically integrated into future UM assessments to better express relations among resource intensity/availability and the configuration of OSN in vulnerable communities. This can enable researchers, practitioners and planners to jointly work toward decision-making and design strategies that could better respond to communities' ambitions toward more resilient and sustainable cities.

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SUPPORTING INFORMATION

This supporting information provides supplementary material that complements the methods and findings included in the main research article, including the compiled GIS datasets used in the study, the criteria and sub-criteria used to classify the boroughs, the Borough Pattern Scan detailed calculation by criteria, and a set of maps and tables including details of the selected boroughs analysis by resource flow type.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and its supporting information.

FIGURE AND TABLE LEGENDS

Table 1: Evaluation and classification of all criteria and sub-criteria used in the analysis by borough. Highlighted in red are values 10% above the average, in orange the average values, and in gray the values 10% below the average.

Figure 1. The geographic location of Mexico City and its 16 boroughs subdivision. The Metropolitan Zone of the Mexico Valley including the states of Mexico and Hidalgo. Mexico City including topography, administrative boundaries, informal settlement areas (red contour lines), indigenous areas (white contour lines) and communal lands (blue contour lines). The Conservation Land (with green contour lines) delimits the urban and rural areas in the city.

Figure 2: Resource efficiency framework diagram.

Figure 3: Spatial distribution of drinking water and sewage system flows and infrastructure. Water consumption and wastewater outflows are quantified by borough. The location of infrastructure, resource management facilities and main networks for drinking water and sewage system are highlighted with specific symbols and colors by type.

Figure 4: Spatial distribution of electrical energy flows and infrastructure. Electricity consumption is quantified by borough. The locations of the infrastructure, resource management facilities and main distribution network are highlighted with specific symbols and colors by type.

Figure 5: Spatial distribution of solid waste flows and infrastructure. Municipal solid waste (MSW) and construction solid waste (CSW) are quantified by borough. Locations of the

infrastructure and resource management facilities are highlighted with specific symbols and colors by type.

Figure 6: Spatial distribution of the OSN (Figure 6.a) and the vulnerable communities, communal lands, and indigenous areas (Figure 6.b).

Figure 7: Borough Pattern Scan results by type of resource flow. Synthesis map overlapping resource infrastructures, geographic features (including public OSN and productive landscapes), vulnerable communities, communal lands, and indigenous areas.