



Carbon and nitrogen content in Mexico City: evidence of the influence of urban social structure

Contenidos de carbono y nitrógeno en la Ciudad de México: evidencias de la influencia de la estructura social urbana

Research Article

2026 July - December

versión original aquí

R. ISELA JASSO-FLORES Universidad Nacional Autónoma de México, México
isela.jasso.flores@gmail.com**DIEGO CARMONA** Universidad Autónoma de Yucatán, México
diego.carmona@correo.uady.mx**SALOMÓN GONZÁLEZ** Universidad Autónoma Metropolitana, México
sgonzalez@cua.uam.mx**ROGELIO O. CORONA-NÚÑEZ** Universidad Autónoma Metropolitana, México
rogeliocoronan@yahoo.com.mx

ABSTRACT Globally, urban ecosystems are key to mitigating climate change. However, studies focus on developed countries, with few studies in Latin American cities. In this study, we modeled the carbon and nitrogen contents in vegetation and soil in Mexico City and evaluated how urban social inequality (social and economic development; form and structure; and functional typology of residential land uses) influences their contents. Our results indicate that lower social classes and high population densities have the lowest estimates of carbon and nitrogen. In contrast, middle and upper-middle social classes (property and construction prices) show the highest values of carbon and nitrogen. This knowledge is essential for understanding the impacts of urbanization and designing more sustainable urban planning strategies in the face of global environmental change.

RESUMEN A nivel mundial, los ecosistemas urbanos son clave para mitigar el cambio climático. Sin embargo, los estudios se centran en países desarrollados, con escasos estudios en las ciudades latinoamericanas. En este estudio, modelamos los contenidos de carbono y nitrógeno en vegetación y suelo de la Ciudad de México, y evaluamos cómo influyen en sus contenidos la desigualdad social urbana (desarrollo social y económico; la forma y estructura; y la tipología funcional de los usos de suelo habitacionales). Nuestros resultados indican que las clases sociales menos favorecidas y altas densidades poblacionales tienen las menores estimaciones de carbono y nitrógeno. Por el contrario, clases sociales medias y medias altas (precio del predio y construcción) muestran los valores más altos de carbono y nitrógeno. Este conocimiento es esencial para comprender los impactos de la urbanización y diseñar estrategias de planificación urbana más sostenibles frente al cambio ambiental global.

Received: 29/04/2025
Reviewed: 24/08/2025
Accepted: 10/12/2025
Published: xx/xx/2026

KEYWORDS forest biomass, planning, sustainability, urban ecology, urbanization

PALABRAS CLAVE biomasa forestal, ecología urbana, planificación, sostenibilidad, urbanización



Cómo citar este artículo/How to cite this article: Jasso-Flores, I. R., Carmona, D., González, S., y Corona-Núñez, R. (2026). Contenidos de carbono y nitrógeno en la Ciudad de México: evidencias de la influencia de la estructura social urbana. *Estoa. Revista de la Facultad de Arquitectura y Urbanismo de la Universidad de Cuenca*, 15(30), e5974. <https://doi.org/10.18537/estv015.n030.a05>

1. Introduction

1.1. Cities and their global importance

The World Bank indicates that 56% of the world's population lives in cities, and by 2050, this figure will exceed 70% (Schrader-King, 2023). This urban growth, which is generally unsustainable, promotes the degradation of ecosystems and rural landscapes, reducing biodiversity, ecosystem services, and the capacity of cities to store carbon in soils and vegetation, which limits their resilience to climate change (Martínez-Castrejón and Hernández-Flores, 2025; Flores-Reyes et al., 2025; Jasso-Flores et al., 2025).

As cities continue to grow, it is necessary to address access to adequate, affordable housing for the population (Rolnik, 2019) and to implement strategies that promote sustainable land management to achieve global sustainability goals (Wu et al., 2024). In this regard, the dynamism of cities and their environmental impacts should be addressed from a socioeconomic and political perspective (Yang et al., 2025). As Lefebvre (1991) and Harvey (2003) warn, the production of urban space is linked to socioeconomic structures that perpetuate inequalities and environmental degradation, so any sustainability strategy must consider these dynamics in order to be effective. However, the lack of public policy to help mitigate and/or prevent the loss of ecosystem services will reinforce urban unsustainability (Spiliotopoulou and Roseland, 2020) and intensify climate change.

1.2. Socio-spatial inequality and urban sustainability

Urban sustainability is understood as an adaptive process that integrates social and economic equity and environmental resilience, including governance (Perrotti, 2020). In this framework, urban space ceases to be a mere physical container and is recognized as a social construct that reflects and reproduces structural inequalities (Lefebvre, 1991). Furthermore, in the face of environmental challenges, there is a pressing need to seek sustainable urban environments that increase well-being and reduce social and environmental inequalities (Harvey, 2003). For this reason, initiatives such as the New Urban Agenda, the International Guidelines on Urban and Territorial Planning, and the Paris Agreements linked to the Sustainable Development Goals have been promoted at the international level. However, questions remain about cities' capacity to mitigate climate change (Kumar et al., 2025).

Cities and their constant expansion drive demand for goods and services, promoting social inequality (Rolnik, 2019) and degrading natural and rural landscapes (Cárdenas-Mamani and Perrotti, 2022), which, in turn, reinforces climate change. Thus, the reconfiguration of geographical space and urban (un)sustainability are closely related. Climate change mitigation can therefore be addressed by redesigning, creating, and consolidating cities based on criteria of resilience and equity (Henderson, 2003; Perrotti, 2020). Furthermore, it must be accompanied by a critique of the dominant economic model, which instrumentalizes urban space as a commodity and deepens environmental and social crises (Harvey, 2003), in order to strengthen the factors that mitigate climate change and reverse those that aggravate it. In this context, our research focuses on assessing how social inequality in urban and rural environments characterizes above-ground and below-ground carbon and nitrogen stores.

1.3. The dynamics of carbon and nitrogen in urban and rural soils

Urban and rural soils constitute a complex system where various factors, such as irrigation patterns (Zhang et al., 2022a), vegetation management practices, and mechanical soil removal (Cotler et al., 2024; Wu et al., 2024), determine the capacity of vegetation to sequester and store carbon and nitrogen (Canedoli et al., 2020). Furthermore, urban space cannot be understood solely in terms of its physical dimension, but rather as a social construct that reflects structural inequalities. These inequalities are not accidental, but rather the result of historical urbanization processes linked to the dominant economic model, which exploits the territory and deepens the environmental crisis (Jasso-Flores et al., 2025; Harvey, 2003). Furthermore, although it is recognized that social inequalities directly influence patterns of use and distribution of ecosystem services (Lefebvre, 1991; Rolnik, 2019), in the particular case of Latin America, these approaches are rare.

1.4. Methodological challenges in urban sustainability

Spatial variability associated with land use and urbanization complicates direct measurement of carbon and nitrogen beneath streets and buildings. Therefore, indirect approaches are required to estimate these values and assess the impact of urban expansion. In developed countries, methodological frameworks have been developed that combine field measurements, remote sensing, and spatial modeling to simultaneously quantify carbon and nitrogen reserves in soil and vegetation (Pataki et al., 2011; Vaccari et al., 2013; Yuzugullu et al., 2024). However, these studies focus on green infrastructure in cities or on rural land, limiting our understanding of the influence of urban social structure (Canedoli et al., 2020; Guo et al., 2024).

This methodological limitation is even more evident in the Latin American context, where theoretical and technical gaps persist regarding the carbon cycle in cities. In Mexico, for example, most studies have focused on emissions estimates without considering the role of urban vegetation. In contrast, others are restricted to specific soil sampling (Cotler et al., 2024), without articulating the natural components with the social structures that shape the urban landscape. This situation reflects the fact that there are still major questions about the influence of urban structure on carbon and nitrogen content. That is why the objective of this study is to evaluate the influence of the social structure of urban landscapes on soil and vegetation carbon and nitrogen in Mexico City. We selected Mexico City because it is the largest urban agglomeration in Mexico, with a population of 9.2 million (Mendoza-Ponce et al., 2019).

2. Methods

2.1. Delimitation and territorial characterization

Mexico City is located at an altitude of 2,200–3,900 meters above sea level. Its predominant climate is temperate subhumid, and the vegetation includes temperate forest, scrub, and hydrophilic vegetation.

Inside the urban area, introduced plant species such as cypresses, eucalyptus, ficus, and palm trees predominate. In contrast, relics of native vegetation are preserved on the outskirts and in rural areas where agricultural and livestock activities are carried out (Vela Correa et al., 2012). Administrative and political power is mainly concentrated in the city center (Zócalo), within the Cuauhtémoc Mayor's Office.

The delimitation of residential land uses in Mexico City is restricted to urban and rural areas, which exhibit contrasting socioeconomic gradients from the city center to its periphery (Table 1). The morphological typology used in this study is based on the characteristics of exclusively residential land use, built-up areas, land use of urban structures, and their centrality, according to the official definitions of the Mexico City Government (IPDP, 2020). We use this typology because it enables us to link the results of this research to current public policy and land-use planning. In addition, this typology allows us to evaluate the influence of the urban social structure on the carbon and nitrogen content of soil and vegetation.

2.2. Data analysis

Landsat satellite images from 2014, climate and topographic data, and forest sampling were used to estimate atmospheric carbon stocks. Climate data was obtained from Worldclim (Fick and Hijmans, 2017). Satellite data were processed using various vegetation indices. Field forest sampling was carried out in 2014 by the Mexican Forestry Commission (CONAFOR, 2012). Each sampling point includes dasometric measurements for each forest individual (height and diameter). For this study, forest biomass was estimated using allometric equations. Forest biomass was transformed into above-ground carbon stocks. Subsequently, geostatistical modeling was performed to reconstruct vegetation carbon stocks, using satellite, topographic, and climatic information as independent variables. These variables were selected because they show a close relationship with forest carbon dynamics (Corona-Núñez et al., 2021).

	Typology	Definition
1	Rural housing	Consists of low-density single-family or multi-family housing, with low-impact commerce and/or basic services. Located within the rural environment of Mexico City.
2	Peri-urban housing	This consists of low- to medium-density single-family or multi-family housing, with low-impact commerce and/or basic services. It is located within the peri-urban environment of Mexico City.
3	Urban housing (low and medium)	Consists of single-family or multi-family housing with low-impact commerce and/or services on the ground floor. Depending on the size of the property and added value, it includes low and middle social classes, with average construction sizes <500 m ² .
4	Urban housing (upper-middle and upper)	Consists of single-family or multi-family housing with low-impact commercial and/or service establishments on the ground floor. Depending on the size of the property and its added value, it includes upper-middle and upper social classes, with average construction sizes ≥500 m ² .

Table 1: Definitions of urban and rural residential land use typologies. The definitions were obtained from the Mexico City General Land Use Planning Program Project. (IPDP, 2020)

Information from Poggio et al. (2021) was used to estimate soil carbon stocks and nitrogen concentrations at 0-30 cm depth. However, this information only focuses on portions of the territory with vegetation cover in natural and rural areas. To supplement the information in peri-urban and urban areas, interpolation was necessary. Carbon stocks in vegetation were used as a component of soil carbon and nitrogen modeling, complemented by climatic and topographic information. These variables were selected because they have been shown to drive soil carbon and nitrogen dynamics (Vasenev et al., 2014). Estimates of carbon stocks and soil nitrogen concentrations reflect baseline values, not those enriched by anthropogenic activities such as fertilization or environmental pollution.

Geostatistical analyses were performed using Random Forest (Breiman, 2001). Random Forest is an automated machine learning algorithm that constructs multiple decision trees by iteratively selecting observations and variables for prediction (Guzmán-Santiago et al., 2024). Finally, it integrates all decision trees to reduce overfitting. This methodological approach has shown good results in other similar urban studies (Li et al., 2023).

To understand the influence of the socioeconomic level of the socio-residential structure on carbon and nitrogen, it was necessary to address them in three ways: (1) At the municipal level, social and economic development was evaluated through the number of inhabitants, gross domestic product (GDP), population density, and GDP per capita (INEGI, 2020; Mendoza-Ponce et al., 2019), the Social Development Index (number of people in the "low and very low" classes), the Marginalization Index, and the employed population earning less than two minimum wages (total and percentage) (CONAPO, 2021). These socioeconomic variables were selected because they capture both the economic resources available and the levels of social vulnerability that condition land-use decisions. (2) At the municipal level, urban form and structure were evaluated. Urban form and structure refer to how physical and functional elements are organized and distributed within a city, including the layout, form, and connectivity of housing, as well as conditions that influence the city's economic development and social needs (Álvarez de la Torre, 2017). Urban form and structure are related to urban sustainability, as urban transformation processes influence the reconfiguration of human settlements and the behavior of inhabitants (Zumelzu-Scheel, 2016). The variables used to assess social inequality from the urban structure and form were: average year of construction, centrality, land-use coefficient (LUC), proportion of the municipality with conservation land, average construction area, and average land value (m^2 and property). The analysis of the influence of centrality as a socioeconomic metric was defined based on the average distance of each municipality from the Zócalo. And (3) at the local level, social inequality was assessed through the functional typology of urban and rural residential land uses (Table 1). The selected housing typology allows for the differentiation of housing socioeconomic conditions in Mexico City by grouping land uses according to economic indicators, services, and infrastructure quality, etc. (Table 1), as defined by the same authority, thus maintaining objectivity in the integration of results.

Linear regressions, the coefficient of determination (r^2), and its significance (p-value) were used to assess the influence of social and economic development and urban form and structure on carbon and nitrogen metrics. The statistical characterization and comparison of different urban and rural land uses were performed using the Wilcoxon rank-sum test and violin plots. All analyses were performed using R.

3. Results

3.1. Characterization of Mexico City

On average, the median size of the boroughs is $92.8 \pm 86.9 \text{ km}^2$. The smallest borough is Benito Juárez (26.68 km^2), and the largest is Tlalpan (314.25 km^2) (Table 2). On average, the properties' surface area is $287 \pm 199 \text{ m}^2$, while the buildings' surface area is $1,938 \pm 58 \text{ m}^2$. The average value per m^2 is $3,498 \pm 2,054$ Mexican pesos (\$), ranging from \$611 to \$8,177 in Milpa Alta and Miguel Hidalgo, respectively.

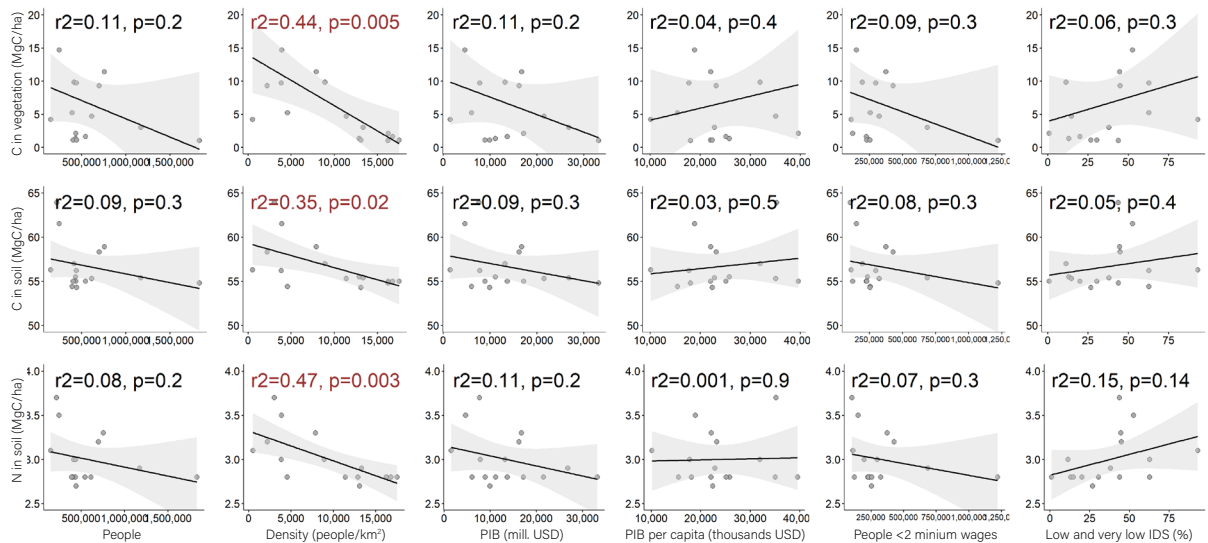


Figure 1: Carbon stocks in vegetation and soil, and nitrogen concentration in soil in relation to the main social and economic variables at the municipal level. Statistically significant relationships are highlighted in red. (2025)

3.3. Influence of the urban form and structure of municipalities

The average value per property is \$ 656,491 ± \$315,969. The boroughs with the highest number of people are Gustavo A. Madero (1.17 million people) and Iztapalapa (1.84 million people), while Milpa Alta has 152,700 people. Population density also varies greatly between boroughs. Four boroughs (Benito Juárez, Cuauhtémoc, Iztacalco, and Iztapalapa) exceed 16,000 people per km², and the least populated is Milpa Alta (528 people per km²). The boroughs that contribute most to GDP are Coyoacán, Gustavo A. Madero, and Iztapalapa, while the least are Milpa Alta and Tláhuac. This contrasts with GDP per capita, where the richest boroughs are concentrated in Benito Juárez, Coyoacán, Cuajimalpa de Morelos, and Miguel Hidalgo, while the poorest are Milpa Alta and Tláhuac. Only one borough has less than 40% of its population employed with incomes below two minimum wages. Official statistics indicate that all boroughs have a “very low” marginalization index.

3.2. Influence of the social and economic development of the boroughs

The number of people per borough, GDP, and the number of employed people with incomes <2 minimum wages show an inverse relationship with carbon and nitrogen metrics. However, none of them are significant ($r^2 < 0.11, p > 0.2$). Per capita GDP and the social development index (SDI) show a positive relationship, but it is not significant ($r^2 < 0.15, p > 0.1$). The only variable that proved to be statistically significant was population density, which had an inverse relationship with all metrics ($r^2 > 0.35, p < 0.02$) (Figure 1).

Various indicators of urban form and structure show a strong positive relationship with carbon and nitrogen content (Figure 2). Only the CUS shows an inverse but insignificant relationship ($r^2 < 0.14, p > 0.2$). Property value and construction area show a significant relationship ($r^2 > 0.38, p < 0.01$), as does the average year of construction ($r^2 > 0.4, p < 0.01$).

The municipalities with a higher proportion of conservation land are those with the highest levels of carbon and nitrogen ($r^2 > 0.28, p < 0.03$). The municipalities of Cuajimalpa de Morelos and La Magdalena Contreras have vegetation and soil carbon densities above the average for Mexico City. This contrasts with the borough of Milpa Alta, where the entire area is considered conservation land and its average total carbon density ($60.5 \pm 9.1 \text{ MgC ha}^{-1}$) is similar to the average ($58.4 \pm 4.0 \text{ MgC ha}^{-1}$) of boroughs that do not have conservation land.

Centrality has led to a direct positive relationship between carbon and nitrogen content and distance from the Zócalo. The lowest levels of carbon stocks in vegetation (Figure 3a) are observed within 5 km of the Zócalo, where a value of $0.6 \pm 0.2 \text{ MgC ha}^{-1}$ was recorded. These stocks increased to $1.5 \pm 7.5 \text{ MgC ha}^{-1}$ at a distance of 5-15 km, and a maximum of $6.0 \pm 3.4 \text{ MgC ha}^{-1}$ at distances of 15-30 km. The municipality of Milpa Alta, located 34 km away, stands out with an intermediate concentration and an average carbon storage of $4.2 \pm 5.9 \text{ MgC ha}^{-1}$. Soil carbon storage shows little variability with distance from the Zócalo (Figure 3b). However, the lowest stores were recorded at <5 km ($54.7 \pm 0.4 \text{ MgC ha}^{-1}$), followed by a

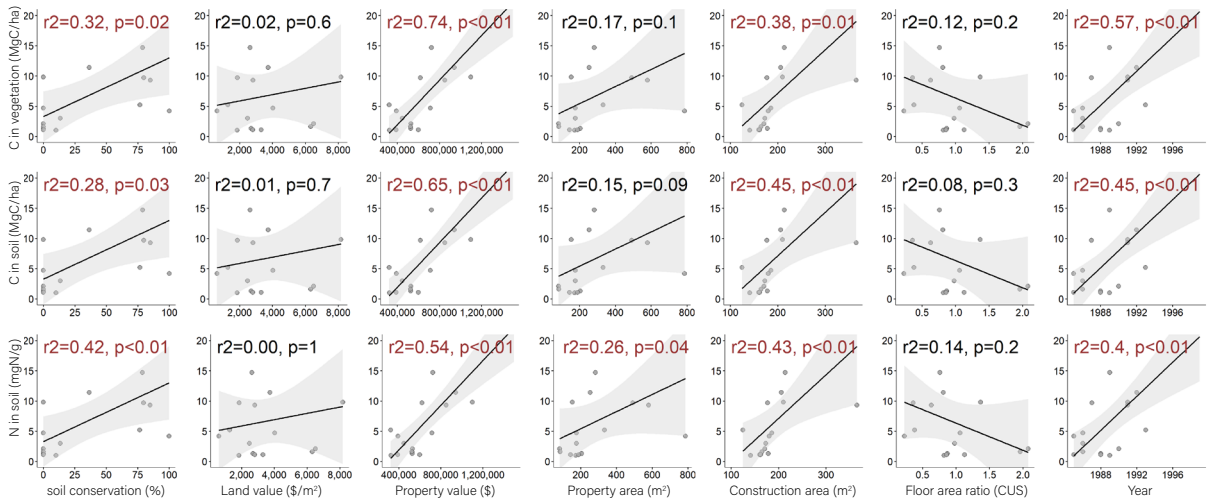


Figure 2: Carbon stores in vegetation and soil, and nitrogen concentration in soil in relation to the main variables of urban form and structure at the borough level. Statistically significant relationships are highlighted in red. (2025)

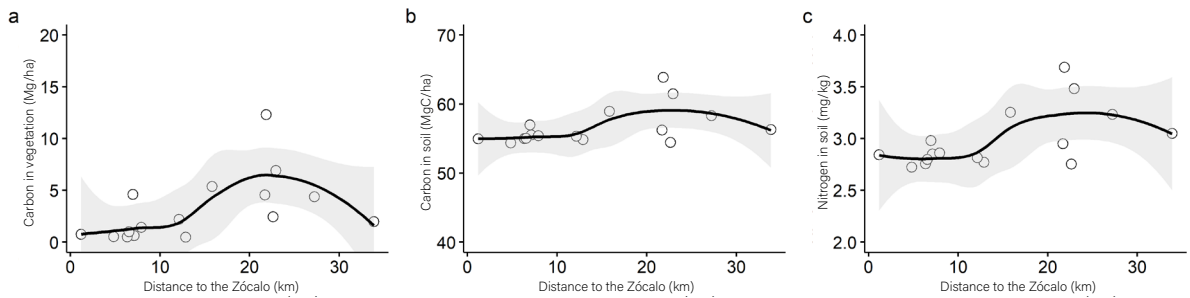


Figure 3: Carbon stores in vegetation (a) and soil (b), and nitrogen concentration in soil (c) in relation to their centrality (average distance to the Zócalo in Mexico City). (2025)

distance of 5-15 km ($55.4 \pm 0.7 \text{ MgC ha}^{-1}$), at distances of 15-30 km ($58.9 \pm 3.4 \text{ MgC ha}^{-1}$), and decreasing at distances $> 30 \text{ km}$ (56.3 MgC ha^{-1}). These trajectories are similar for nitrogen concentrations (Figure 3c), where values of $2.8 \pm 0.1 \text{ mgN g}^{-1}$ were estimated for distances of $< 5 \text{ km}$ and 5-15 km. At distances of 15-30 km, an increase to $3.2 \pm 0.3 \text{ mgN g}^{-1}$ is observed, and from 3.0 mgN g^{-1} to $> 30 \text{ km}$.

3.4. Influence of the functional typology of urban and rural residential land uses

Carbon storage in vegetation varied by land use (Figure 4). Urban areas with medium-high and high socioeconomic levels recorded the highest values, with an average of $6.8 \pm 7.8 \text{ MgC ha}^{-1}$, followed by peri-urban areas ($5.7 \pm 8.2 \text{ MgC ha}^{-1}$) and rural areas ($3.9 \pm 7.6 \text{ MgC ha}^{-1}$). In contrast, urban areas with low and medium socioeconomic levels recorded the lowest values, with storage $< 1.2 \pm 3.4 \text{ MgC ha}^{-1}$, representing a 82.4% reduction compared to urban areas with higher socioeconomic strata.

The results show significant differences in soil carbon storage between different types of residential land use (Figure 5). The highest amount of carbon was recorded in peri-urban areas ($58.9 \pm 6.1 \text{ MgC ha}^{-1}$) and rural areas ($58.6 \pm 5.0 \text{ MgC ha}^{-1}$). In contrast, urban areas (low and medium, and medium-high and high) exhibited the lowest values, with an average storage of 55.7 MgC ha^{-1} , equivalent to a 5.4% reduction compared to their counterparts in peri-urban areas.

The concentration of nitrogen in the soil showed a similar pattern to that of carbon, with the highest concentrations found in rural areas ($3.2 \pm 0.4 \text{ mgN g}^{-1}$) and peri-urban areas ($3.1 \pm 0.4 \text{ mgN g}^{-1}$), followed by medium-high to high-level housing areas ($2.9 \pm 0.1 \text{ mgN g}^{-1}$) and the lowest values in low and medium levels ($2.8 \pm 0.2 \text{ mgN g}^{-1}$) (Figure 6).

Municipality	Conservation land (%)	Carbon in vegetation (MgC ha ⁻¹)	Carbon in soil (MgC ha ⁻¹)	Nitrogen in soil (mgN g ⁻¹)	Soil carbon: vegetation ratio
Álvaro Obregón	36.4	11.4±18	58.9±4	3.3±0.4	5.2
Azcapotzalco	0.0	1.3±4.1	55.5±1.1	2.8±0.1	42.7
Benito Juárez	0.0	2.1±6.4	55±1.2	2.8±0.1	26.2
Coyoacán	0.0	4.7±9.6	55.3±1.8	2.8±0.1	11.8
Cuajimalpa de Morelos	76.2	26.2±28.4	63.9±5.2	3.7±0.3	2.4
Cuauhtémoc	0.0	1.6±5.3	55±1.3	2.8±0.1	34.4
Gustavo A. Madero	13.4	3.0±7.6	55.4±1.8	2.9±0.2	18.5
Iztacalco	0.0	1.1±3.2	55±1	2.8±0.1	50
Iztapalapa	10.0	1.0±2.9	54.8±1.3	2.8±0.1	54.8
La Magdalena Contreras	78.8	14.7±19.9	61.5±4.2	3.5±0.3	4.2
Miguel Hidalgo	0.0	9.8±15	57±2.7	3.0±0.3	5.8
Milpa Alta	100	4.2±5.9	56.3±3.2	3.1±0.3	13.4
Tláhuac	76.6	5.2±9.2	54.4±1.4	2.8±0.1	10.5
Tlalpan	84.8	9.3±14.6	58.3±4.1	3.2±0.3	6.3
Venustiano Carranza	0.0	1.1±3.4	54.3±1	2.7±0.1	49.4
Xochimilco	79.6	9.7±13	56.2±2.3	3.0±0.2	5.8
Average	58.9	6.4±13.3	56.4±3.5	3.0±0.3	21.3±18.8

Table 2: Socioeconomic characteristics of Mexico City boroughs. Size refers to the area of the borough. The average land value is reported in Mexican pesos per property. The land use coefficient was calculated as the ratio of built area to total property area. The year of construction refers to the average date of construction in the borough. INEGI, (2020) y Mendoza-Ponce et al. (2019)

Municipality	Size (km ²)	Centrality (km)	Average land value (\$)	Construction area (m ²)	Land use coefficient	Year of construction	Number of people	Gross Domestic Product (millions of dollars)
Álvaro Obregón	95.82	15.83	942,374	206	0.81	1992	759,137	16,788.0
Azcapotzalco	33.50	7.12	526,934	178	0.87	1988	432,205	11,174.4
Benito Juárez	26.68	6.55	529,591	171	2.08	1990	434,153	17,192.6
Coyoacán	53.88	12.14	714,503	186	1.06	1986	614,447	21,560.7
Cuajimalpa de Morelos	71.41	21.86	1,498,678	281	0.58	1999	217,686	7,678.0
Cuauhtémoc	32.50	1.19	524,534	165	1.96	1986	545,884	13,716.9
Gustavo A. Madero	87.84	7.91	446,570	173	0.98	1986	1,173,351	26,830.6
Iztacalco	23.08	6.35	388,595	160	1.13	1988	404,695	8,937.0
Iztapalapa	113.07	12.88	323,604	141	0.82	1989	1,835,486	33,218.4
La Magdalena Contreras	63.37	22.95	724,444	214	0.76	1989	247,622	4,680.4
Miguel Hidalgo	46.36	6.97	1,100,422	210	1.37	1991	414,470	13,259.8
Milpa Alta	289.04	33.87	390,388	180	0.23	1985	152,685	1,550.9
Tláhuac	85.78	22.64	323,194	125	0.38	1993	392,313	6,082.0
Tlalpan	314.25	27.22	851,377	365	0.63	1991	699,928	16,258.2
Venustiano Carranza	33.84	4.82	599,374	162	0.86	1985	443,704	9,947.7
Xochimilco	114.03	21.7	619,273	177	0.36	1987	442,178	7,854.6
Average	92.8	14.5	656,491	193.4	0.93	1989	575,622	13,545.6

Table 3: Environmental characteristics of Mexico City's boroughs. (2025).

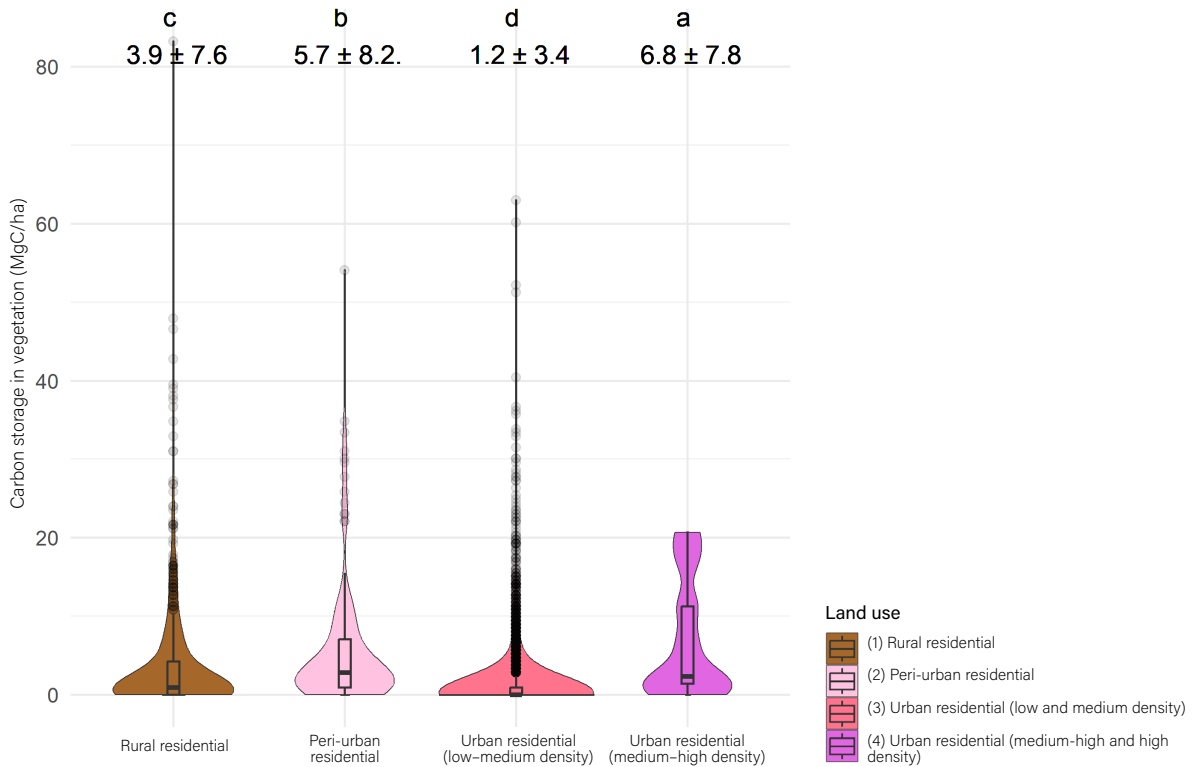


Figure 4: Distribution of carbon stores in vegetation according to the typologies of Mexico City. (2025)

4. Discussions and conclusions

4.1. Influence of social inequality

Mexico City plays a key role in the continuous evolution and transformation of the capital and the country. Historically, the organization and planning of the territory have been the result of reactive responses to social, economic, and political demands, rather than proactive efforts to achieve orderly and sustainable development. This same process of transformation has been directly related to the conservation of ecosystem services.

The structure of urbanization and polarization within Mexico City has generated an urban-rural socioeconomic gradient, in which the proper design and implementation of land-use planning have focused on economically privileged populations (Figure 7; Martínez, 2015). These conditions have generated differential pressures on vegetation cover and soil. The concentration of carbon stores has been restricted to portions of the territory where segregative public policies and socioeconomic status have influenced the conservation of green spaces (Jasso-Flores et al., 2025). However, this dynamic is clearer when analyzing urban form and structure, as well as the functional typologies of urban and rural residential land. For example, there are parts of the territory where high forest density is associated with middle- to upper-class residential areas. Meanwhile, in lower-middle to middle-class residential areas, forest density is low. These conditions have promoted contrasting differences in urbanization processes, resulting in the polarization of urban sustainability, reinforcing socio-spatial inequalities (Rolnik, 2019) and reflected in carbon and nitrogen contents.

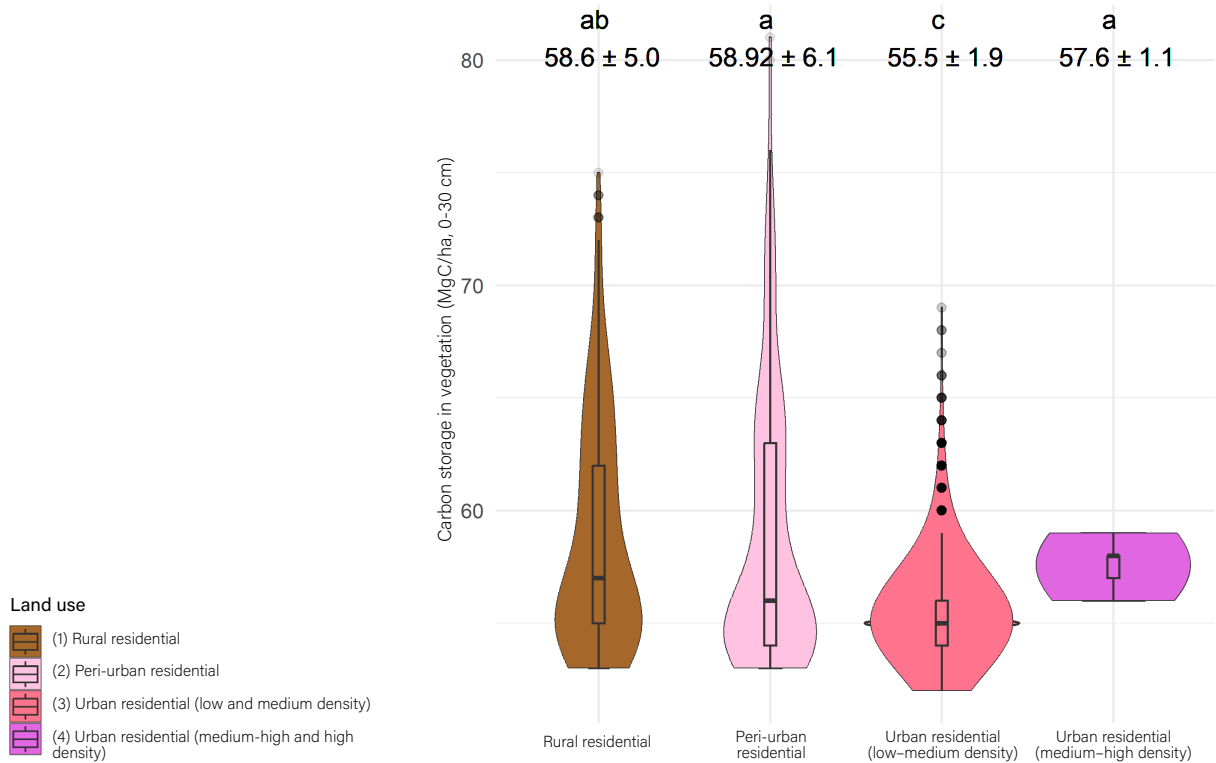


Figure 5: Distribution of soil carbon stores according to housing types in Mexico City. (2025)

4.2. Influence of residential land uses

Urbanization significantly modifies the carbon dynamics in vegetation and soil. Several studies have shown that increased impervious surfaces reduce vegetation cover and, in turn, carbon storage capacity (Cotler et al., 2024). In this study, we show that, in addition to land-use change, a disturbance gradient is associated with the socioeconomic levels of housing use, leading to variations in carbon and nitrogen stores depending on the degree of intensification of anthropogenic activities.

The clearing of vegetation and subsequent soil sealing reduce the potential for carbon sequestration due to the lack of organic matter input from vegetation (Zong-Qiang et al., 2014). In addition, the translocation of construction materials and interventions in green areas affects carbon storage (Cotler et al., 2024; Vasenev et al., 2014). Therefore, revegetation with grasses and trees on ridges promotes carbon recovery in vegetation and soil by reducing erosion of exposed soil and restoring organic matter input to the soil (Kumar et al., 2025). These types of interventions are more common in neighborhoods with greater economic power and lower population density (Jasso-Flores et al., 2025), which reflects an additional challenge for housing design for disadvantaged social groups, particularly in Latin America, as observed by Rolnik (2019).

Deforestation and degradation of natural ecosystems, coupled with a lack of revegetation policies, have left Mexico City with a significant deficit in tree cover, with important differences between boroughs. For example, although Mexico City has a total of 2,643 ha of green areas, this represents only 2.93 m² of green space per person. This value is well below the recommended minimum threshold of 9 m²/person (Ayala-Azcarraga et al., 2023). Taken together, this means that the carbon content in Mexico City is mainly concentrated in its underground component, with soil concentrations on average

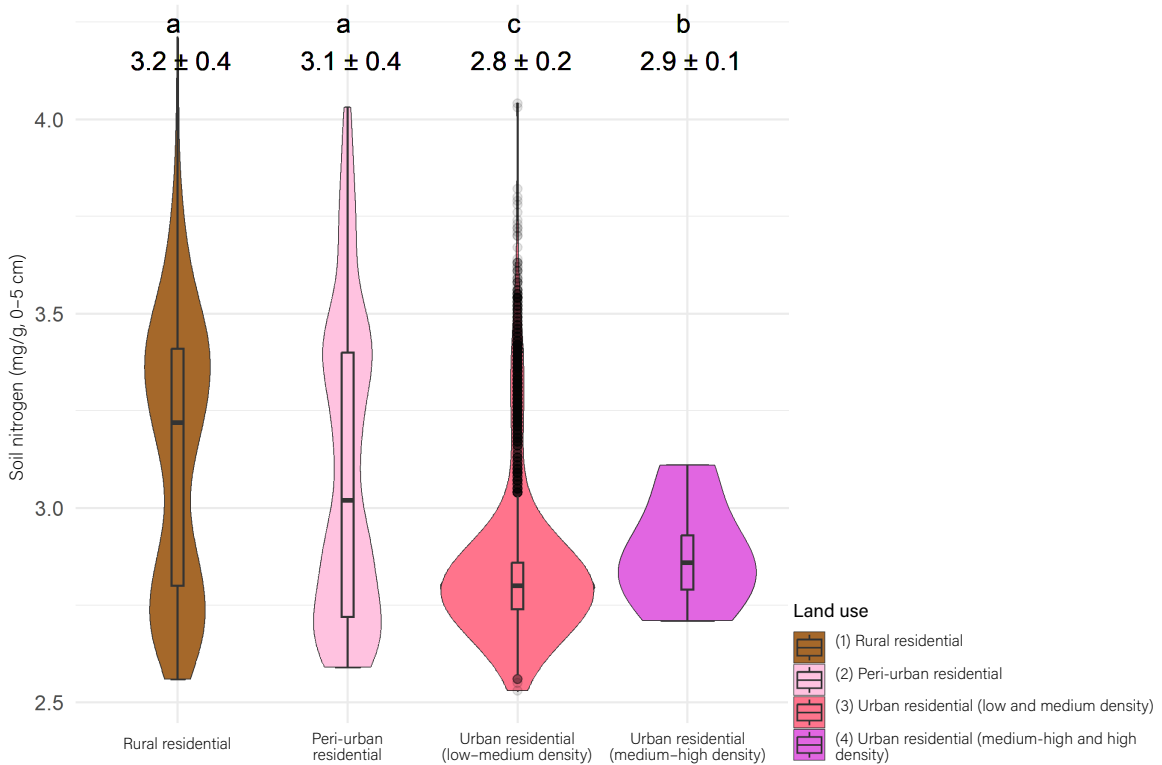


Figure 6: Distribution of nitrogen concentration in soil according to residential typologies in Mexico City. (2025)

21.3±18.8 times higher than those in vegetation. Therefore, inequalities are not only concentrated at the municipal level, but also transcend to differences at the housing level. This situation highlights the need for innovative designs within the framework of urban planning, which not only seeks to create affordable housing for the population but also addresses the global environmental and social crises (Harvey, 2003).

4.2. Implications and alternatives

Despite the importance of quantifying carbon and nitrogen stores in vegetation and soil, these components have been largely neglected in Mexico's urban environments. This is particularly relevant, as urban soils often have a greater carbon storage capacity than vegetation. Although the carbon contained in urban trees has been estimated in various cities, this partial attention has led to an imbalance in knowledge between compartments. In addition, existing studies have focused predominantly on green areas, urban parks, and atmospheric emissions, addressing one of the stores or flows in isolation, without incorporating comprehensive spatial representations (Cotler et al., 2024; Pariente and Zhevelev, 2015; Saavedra-Romero et al., 2020; Velasco et al., 2016). This fragmentation of information limits the understanding of ecosystem

processes and hinders the analysis of the impacts of urbanization on carbon and nitrogen content in the urban landscape.

This study introduces an additional layer of complexity to the components that must be integrated into the urban planning framework, requiring a profound transformation of urbanization models and paradigms. For example, this study highlights a persistent theoretical disconnect between soil as a natural support for ecosystem services and its integration into the urban landscape. Although our results demonstrate the attributable impact of residential land uses, at multiple scales, on carbon and nitrogen content in Mexico City, urban development and territorial planning policies continue to fail to recognize soil as a structural component in their design and management schemes. As Rolnik (2019) warns, it is necessary to rethink urbanism beyond the rationalization and commodification of space, towards a system capable of responding to global challenges. Cities are not isolated entities, but are jointly responsible for impacts that transcend their physical boundaries. This critical view aligns with Lefebvre's (1972; 1991) reflections, which emphasize that the production of urban space is traversed by social and political complexities that are often ignored

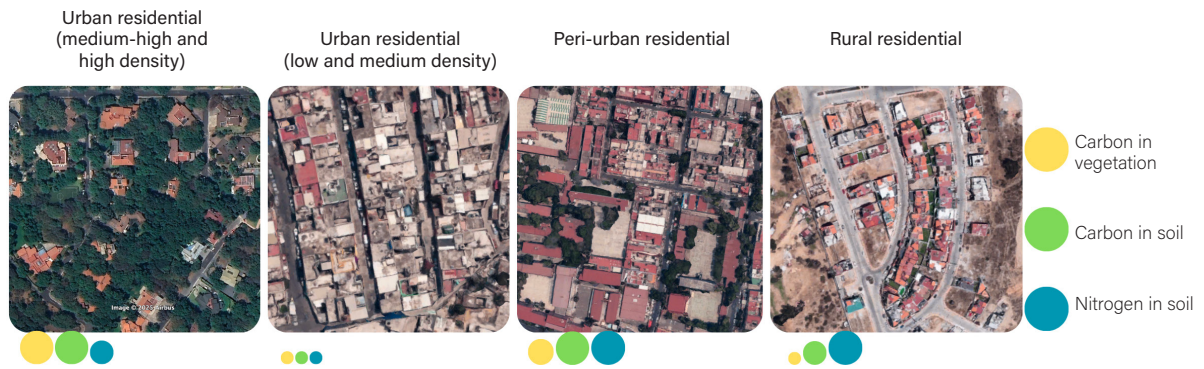


Figure 7: Socioeconomic gradient and carbon and nitrogen content of housing types in Mexico City. Authors (2025) with images from Google Earth (2025)

in urbanization processes. Lefebvre also warned that space is not neutral, but rather a social construction whose implications extend beyond city boundaries, especially under the dynamics of globalization. In this sense, the production of space must be conceived as an open possibility, capable of integrating the reduction of the environmental crisis as part of its fundamental purpose (Harvey, 2003).

In the context of global environmental change, understanding how urban and rural land uses affect soil carbon storage and sequestration is essential for designing land-use planning and management strategies to mitigate climate change (Jasso-Flores and Corona-Núñez, 2025). Sealed urban soil functions as a more stable and durable carbon store than plant biomass, whose accumulation is subject to fluctuations driven by management, climate, and disturbances (Zhang et al., 2022b). Global evidence from old and new cities supports this idea, as older urban regions show higher soil carbon levels. However, focusing solely on the age of urbanized soils for climate change mitigation overlooks the urgent need to conceive of the natural component as a structural element of the urban landscape. As McHarg (1969) posited, modern planning must be based on an understanding of ecological processes in order to articulate the urban fabric with landscape patterns. In this way, soils are not limited to being fill or adornments in specific green areas, but function as active corridors of ecosystem services that traverse and connect all the fabrics of the city.

Additionally, it has been documented that social factors and urban and rural landscape configurations have distinct impacts on carbon stocks. For example, carbon in urban vegetation is closely linked to social variables such as socioeconomic stratification and lifestyles. In contrast, soil carbon responds mainly to land-use and pedogenic factors rather than to vegetation cover, as is the case in natural systems (Guo et al., 2024). This evidence suggests that classifications based on functional land-use structures

offer greater explanatory power for understanding nutrient dynamics in urban contexts than typologies focused exclusively on vegetation, which have historically predominated. Consequently, a comprehensive perspective is needed that articulates the social, urban, and environmental dimensions, enabling the design of more effective and context-specific public policies. This need is particularly urgent in Latin American cities, which remain underrepresented in the literature on urban carbon and nitrogen, despite rapid urbanization and profound socio-environmental inequalities.

5. Recommendations

Internationally, the importance of vegetation and soil for climate change mitigation is well known. Recently, it has been recognized that cities also play a role in mitigating climate change. The 2030 Agenda has highlighted the importance of urban ecosystems as an integral part of mitigation strategies. However, the approaches of developing countries, including Mexico, have focused on studying natural environments, leading to a lack of knowledge about Latin American cities. This knowledge is particularly essential for understanding the impacts of urbanization and the alternatives in city planning processes.

This knowledge gap is critical, given that understanding the impacts of urbanization and its alternatives is essential for guiding more sustainable and equitable urban planning processes. In this sense, the right to the city, from Lefebvre's perspective, emphasizes collective access to goods and services, including the environment, generating a transformation of everyday life. This vision requires urban planning that recognizes structural inequalities and promotes both spatial (Carrión, 2019) and environmental (McHarg, 1969) justice. Therefore, future studies should evaluate not only carbon and nitrogen stores according to urban land use, but should also integrate the effect of construction forms, such as building densities,

differentiating between different types of public spaces, median strips, etc., as strategies that seek to mitigate climate change.

6. Acknowledgments

RIJF and ROCN are grateful for the postdoctoral fellowships awarded by SECIHTI, formerly CONAHCYT, of the Federal Government of Mexico. This work is part of the project funded by CONAHCYT within the framework of Frontera Science (15004) "Cities in transition: spatial dimension of ecological (dis)connection, urban lifestyles, and future scenarios." We would also like to thank the EESU (Evolution and Ecology in Urban Systems) of the Mexican Scientific Society of Ecology for the fruitful discussions that contributed to the design and consolidation of this publication.

Conflict of interest. The authors declares no conflicts of interest.

© **Copyright:** R. Isela Jasso-Flores, Diego Carmona, Salomón González, Rogelio O. Corona-Núñez, 2026

© **Edition copyright:** *Estoa*, 2026.

7. Bibliographic references

- Álvarez de la Torre, G. B. (2017). Morfología y estructura urbana en las ciudades medias mexicanas. *Región y Sociedad*, XXIX(68), 153-191, <https://www.redalyc.org/articulo.oa?id=10250053005>.
- Ayala-Azcarraga, C., Díaz, D., Fernandez, T., Cordova-Tapia, F. & Zambrano, L. (2023). Uneven Distribution of Urban Green Spaces in Relation to Marginalization in Mexico City. *Sustainability* (15), 12652. <https://doi.org/10.3390/su151612652>.
- Breiman, L. (2001). Random forests. *Machine learning*, 45, 5-32. <https://doi.org/10.1023/A:1010933404324>
- Canedoli, C., Ferrè, C., El Khair, D.A., Padoa-Schioppa, E. & Comolli, R. (2020). Soil organic carbon stock in different urban land uses: high stock evidence in urban parks. *Urban Ecosystems*, 23, 159-171. <https://doi.org/10.1007/s11252-019-00901-6>
- Cárdenas-Mamani, Ú. & Perrotti, D. (2022). Understanding the contribution of ecosystem services to urban metabolism assessments: An integrated framework. *Ecological Indicators*, 136, 108593. <https://doi.org/10.1016/j.ecolind.2022.108593>.
- Carrión, F. (2019). El espacio público es una relación no un espacio, En: *Derecho a la Ciudad. Una evocación de las transformaciones urbanas en América Latina*. Eds. Carrión Mena, F., y Dammert-Guardia, M. CLACSO, Flacso – Ecuador, 191-219.
- CONAFOR. (2012). Inventario Nacional Forest y de Suelos 2004-2009. *Protocolo de muestreo de campo*. Comisión Nacional Forestal.
- CONAPO. (2021). *Índice de Marginación a nivel municipal 2020*. CONAPO. <https://www.gob.mx/conapo/documentos/indices-de-marginacion-2020-284372>.
- Corona-Núñez, R. O., Mendoza-Ponce, A. V. & Campo, J. (2021). Assessment of above-ground biomass and carbon loss from a tropical dry forest in Mexico. *Journal of Environmental Management*, 282, 111973. <https://doi.org/10.1016/j.jenvman.2021.111973>
- Cotler, H., Cram, S., Prado, B., Peña, V. & Lucio, L. (2024). Soil Ecosystem Services in Urban Parks as a Basis for Better Urban Planning: The Case of Mexico City. *Spanish Journal of Soil Science*, 14, 13398. <https://doi.org/10.3389/sjss.2024.13398>
- Fick, S. E. & Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), 4302-4315. <https://doi.org/10.1002/joc.5086>
- Flores-Reyes, L. Ramos-Zapata, J. Berkum, P. M. Corona-Núñez, R. O. Estrada-Medina, H.

- Chávez-Pesqueira, M. & Carmona, D. (2025). Urbanization shifts stress-response traits in an alien herb across five tropical cities. *Urban Ecosystems*, 28(3), 103. <https://doi.org/10.1007/s11252-025-01717-3>
- Guo, H., Du, E., Terrer, C. & Jackson, R. B. (2024). Global distribution of surface soil organic carbon in urban greenspaces. *Nature communications*, 15(1), 806. <https://doi.org/10.1038/s41467-024-44887-y>
- Guzmán-Santiago, J. C. Santos-Posadas, H. Ángeles-Pérez, G. Vargas-Larreta, B. Gómez-Cárdenas, M. Rodríguez-Ortiz, G. & Corona-Núñez, R. O. (2024). Effect of climate change on the distribution of temperate climate species in Oaxaca, Mexico. *Botanical Sciences*, 102(1), 39-53. <https://doi.org/10.17129/botsci.3355>
- Harvey, D. (2003). *The new imperialism*. Edit. Oxford University Press.
- Henderson, V. (2003). The urbanization process and economic growth: The so-what question. *Journal of Economic Growth*, 8(1), 47-71. <https://doi.org/10.1023/A:1022860800744>
- INEGI. (2020). *Población rural y urbana*. https://cuentame.inegi.org.mx/poblacion/rur_urb.aspx?tema=P.
- IPDP. (2020). *Proyecto del Programa General de Ordenamiento Territorial de la Ciudad de México 2020-2035*. Instituto de Planeación Democrática y Prospectiva, <https://www.tjacadmx.gob.mx/images/convocatoria-indigena-2022/7.%20Proyecto%20Programa%20General%20de%20Ordenamiento%20Territorial%202020-2035.pdf>.
- Jasso-Flores, I. & Corona-Núñez, R. O. (2025). Recovery of carbon dynamics, soil nutrients and tree diversity during secondary succession within the tropical dry forests in the Yucatán Peninsula. *Journal of Environmental Management*, 394, 127345. <https://doi.org/10.1016/j.jenvman.2025.127345>
- Jasso-Flores, R. I., Escobar-Chanona, L. & Corona-Núñez, R. O. (2025). The colonial and the porfiriato urbanization: inheritance of urban (un)sustainability in Mexico City. *Estoa. Journal of the Faculty of Architecture and Urbanism*, 14(27), 83-96. <https://doi.org/10.18537/est.v014.n027.a05>
- Kumar, P., Sahani, J., Corada Perez, K., Ahlawat, A., Andrade, M., Athanassiadou, M., & Yao, R. (2025). Urban greening for climate resilient and sustainable cities: grand challenges and opportunities. *Frontiers in sustainable cities*, 7, 1595280, <https://doi.org/10.3389/frsc.2025.1595280>.
- Lefebvre, H. (1972). *La revolución urbana*. Edit. Alianza.
- Lefebvre, H. (1991). *The production of space*. Edit. Blackwell.
- Li, F., Yigitcanlar, T., Nepal, M., Nguyen, K., & Dur, F. (2023). Machine learning and remote sensing integration for leveraging urban sustainability: A review and framework. *Sustainable Cities and Society*. (96), 104653, <https://doi.org/10.1016/j.scs.2023.104653>
- Martínez, G. U. (2015). Algunas formas de negociación de los sectores populares ante los juzgados civiles de la ciudad de México en las primeras décadas del siglo XX. *Trashumante: Revista Americana de Historia Social*, (6), 82-103, <https://www.redalyc.org/pdf/4556/455644906005.pdf>
- Martínez-Castrejón, M. y Hernández-Flores, G. (2025). Sustentabilidad urbana de la mano de la naturaleza. Sustentabilidad urbana de la mano de la naturaleza. *Revista Ciencia UANL*, 28(131), 8-15. <https://doi.org/10.29105/cienciauanl28.131-1>.
- McHarg, I. (1969). *Design with nature*. Garden City, N.Y. American Museum of Natural History.
- Mendoza-Ponce, A. V., Corona-Núñez, R. O., Galicia, L. & García-Guerrero, V.M. (2019). Population and economic projections under different scenarios for Mexico. *Papeles de población*, 25(99), 9-43. <https://doi.org/10.22185/24487147.2019.99.02>
- Pariante, S. & Zhevelev, H. M. (2015). Urban park soil and vegetation: Effects of natural and anthropogenic factors. *Pedosphere*, 25(3), 392-404. [https://doi.org/10.1016/S1002-0160\(15\)30007-2](https://doi.org/10.1016/S1002-0160(15)30007-2)
- Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., Pouyat, R. V., Whitlow, T. H. & Zipperer, W. C. (2011). Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, 9(1), 27-36. <https://doi.org/10.1890/090220>
- Perrotti, D. (2020). Chapter 2. Urban metabolism: old challenges, new frontiers, and the research agenda ahead. En P.S.P. Verma, R. Singh, y A.S. Raghubanshi (Ed.), *Urban Ecology* (pp. 17-32): Elsevier. <https://doi.org/10.1016/B978-0-12-820730-7.00002-1>
- Poggio, L., De Sousa, L. M., Batjes, N. H., Heuvelink, G. B., Kempen, B., Ribeiro, E. & Rossiter, D. (2021). SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *Soil*, 7(1), 217-240. <https://doi.org/10.5194/soil-7-217-2021>
- Rolnik, R. (2019). *Urban Warfare. Housing under the Empire of Finance*. Verso.
- Saavedra-Romero, L. L., Alvarado-Rosales, D., Martínez-Trinidad, T. y Hernández-de la Rosa, P. (2020). Propiedades físicas y químicas del suelo urbano del Bosque San Juan de Aragón, Ciudad de México. *Terra Latinoamericana*, 38(3), 529-540. <https://doi.org/10.28940/terra.v38i3.644>

- Schrader-King, K. (2023). *Desarrollo Urbano*, <https://www.bancomundial.org/es/topic/urbandevelopment/overview#1>.
- Spiliotopoulou, M. & Roseland, M. (2020). Urban Sustainability: From Theory Influences to Practical Agendas. *Sustainability*, 12(18), 7245. <https://doi.org/10.3390/su12187245>
- Vaccari, F. P., Gioli, B., Toscano, P. & Perrone, C. (2013). Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning. *Landscape and Urban Planning*, 120, 138-146. <https://doi.org/10.1016/j.landurbplan.2013.08.004>
- Vasenev, V., Stoorvogel, J., Vasenev, I. & Valentini, R. (2014). How to map soil organic carbon stocks in highly urbanized regions? *Geoderma*, 226, 103-115. <https://doi.org/10.1016/j.geoderma.2014.03.007>
- Vela Correa, G., López Blanco, J. y Rodríguez Gamiño, M.L. (2012). Niveles de carbono orgánico total en el Suelo de Conservación del Distrito Federal, centro de México. *Investigaciones geográficas*, 77, 18-30, https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0188-46112012000100003
- Velasco, E., Roth, M., Norford, L. & Molina, L.T. (2016). Does urban vegetation enhance carbon sequestration? *Landscape and Urban Planning*, 148, 99-107. <https://doi.org/10.1016/j.landurbplan.2015.12.003>
- Wu, B., Zhang, Y., Wang, Y., Lin, X., Wu, Y., Wang, J. & He, Y. (2024). Urbanization promotes carbon storage or not? The evidence during the rapid process of China. *Journal of Environmental Management*, 359, 121061. <https://doi.org/10.1016/j.jenvman.2024.121061>
- Yang, Z., Wu, J., Shang, X., Fu, R., Xie, L., & Ge, Q. (2025). Scaling laws of CO₂ emissions during global urban expansion. *npj Urban Sustainability*, 5(1), 3, <https://doi.org/10.1038/s42949-024-00172-x>.
- Yuzugullu, O., Fajraoui, N., Don, A., & Liebisch, F. (2024). Satellite-based soil organic carbon mapping on European soils using available datasets and support sampling. *Science of Remote Sensing*, 9, 100118, <https://doi.org/10.1016/j.srs.2024.100118>.
- Zhang H. L., Nizamani M. M., Cubino J. P., Guo L. Y., Zhou J. J. & Wang H. F. (2022a). Spatiotemporal variation of urban plant diversity and above ground biomass in Haikou, China. *Biology*, 11(12), 1824. <https://doi.org/10.3390/biology11121824>
- Zhang, Z., Gao, X., Zhang, S., Gao, H., Huang, J., Sun, S. & Xia, X. (2022b). Urban development enhances soil organic carbon storage through increasing urban vegetation. *Journal of Environmental Management*, 312, 114922. <https://doi.org/10.1016/j.jenvman.2022.114922>
- Zong-Qiang, W., Shao-Hua, W., Sheng-Lu, Z., Jing-Tao, L. & Qi-Guo, Z. (2014). Soil organic carbon transformation and related properties in urban soil under impervious surfaces. *Pedosphere*, 24(1), 56-64. [https://doi.org/10.1016/S1002-0160\(13\)60080-6](https://doi.org/10.1016/S1002-0160(13)60080-6)
- Zumelzu-Scheel, A. (2016). Forma urbana y sostenibilidad: pasado, presente y desafíos. Una revisión. *Revista AUS*, (20), 77-85, <https://www.redalyc.org/articulo.oa?id=281750069012>.