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Assessing climate change risk: An index proposal for Mexico City

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ABSTRACT

This article reviews risk indices and indicators to explore different ways of measuring urban vulnerability and risk to climate change. The compilation of these indices and indicators allowed the construction of a toolbox (with indicators of hazard, exposure, sensitivity, adaptative capacities, and vulnerability), which offers a consistent conceptual and methodological framework and a set of potentially valuable indicators that may guide future research. Such toolbox is put into practice with the development of an Urban Risk Index for Climate Change (URICC) tested for Mexico City. To develop the URICC, indicators were chosen from the toolbox that were significant for the case study, repeated in at least two of the reviewed works, and with data availability. The URICC –measured at the municipal level and the Basic Geostatistical Areas–, evaluates advances or setbacks concerning the national goal of reducing 50% vulnerability to climate change by 2030 and offers a comparative analysis of climate change risk by 2030 among the 16 municipalities that comprise Mexico City. The findings show that Milpa Alta municipality will experience the most significant setbacks by 2030, while Iztapalapa encounters the highest risk across municipalities. The methods and scales used to assess risk are determinant in producing different results. Assessing risk at the finest scale possible allows identifying specific neighborhood requiring priority interventions. We conclude by reflecting on how the conceptual evolution from vulnerability to risk has impacted the elaboration of risk indices and on the strengths and limitations of our framework.

1. Introduction

Climate change is unequivocal: global emissions of greenhouse gases (GHG) reached 55.3 gigatons of carbon dioxide (CO_2) in 2018 [106], increasing the global annual average temperature by 1 °C compared to pre-industrial levels [60]. This has caused, among other things, the melting of glaciers, sea-level rise, as well as the warming and acidification of the oceans [59]. Climate change has already started to impact humans, and the effects of extreme weather events are likely to increase in the future [61]. Hence, it is crucial to learn how human settlements can adapt to the effects of climate change. Those transitions and the generation of adaptation measures –to adjust to the climate and its effects– are essential in urban settlements in the Global South, where poverty and social inequality exacerbate vulnerability to climate impacts [12].

As the World Health Organization warns, heatwaves, droughts, and storms will impact cities to a greater or lesser extent according to their latitudinal, demographic, biophysical, social, cultural, and political characteristics [111]. Measuring urban climate impacts depends on how vulnerability and climate risk are understood, determined by the chosen conceptual and methodological approach: biophysical, social, economic, political, or hybrid [46]. For this reason, it is important to know how the approach, understanding, and, consequently, frameworks of climate vulnerability and risk have evolved and their link with the prevention and management of urban risk.

Indicator systems are relevant for assessing progress or setbacks in addressing climate impacts in cities [73]. However, their generation and interpretation reveal a tension between political and technical aspects. Indeed, civil servants, experts, and even representatives of funding bodies have different biases and agendas that may be reflected in the overall design and focus of indicators [75,92]. The unequal involvement of different stakeholders and the power relations affecting their

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participation also produce biases in elaborating the indicator that may affect decision-making processes [8]. For instance, an indicator or weighting system can minimize or enlarge the importance of specific dimensions of risk or obscure or shed light on existing inequalities [24].

This article aims, on the one hand, to identify the different ways of measuring urban vulnerability and risk to climate change in order to develop a toolbox that allows future studies to use the same methodological framework. And on the other hand, it develops an Urban Risk Index for Climate Change (URICC) for Mexico City, based on selected indicators from the toolbox relevant to the case study, to serve as an input for disaster risk management at the local level. We understand disaster risk management as the process for designing, implementing, and evaluating strategies, policies, and measures for disaster preparedness, response, and recovery [60].

The article is organized as follows. In section 2, we review the conceptual evolution of the terms "vulnerability" and "risk" within the framework of the IPCC assessment reports, and the methodological development with a brief recount of the state of the art of vulnerability and risk indices, with emphasis on those at the urban level. In section 3, we explain the construction of the toolbox and the evaluation of the URICC. The results of the URICC are shown in section 4. Section 5 discusses the importance of being transparent on the methods used to assess risk and the pertinence of assessing risk at the finest scale possible. Finally, section 6 concludes the paper by reflecting on the strengths and limitations of our framework, and reviewing how the conceptual evolution from vulnerability to risk has been uptaken in the elaboration of risk indices.

2. Review of previous work

2.1. Conceptual evolution of "vulnerability" and "risk" within the IPCC

In the literature, three main conceptual frameworks of vulnerability have been identified [40]. The first is the risk-hazard framework, characteristic of technical assessments of risk and disaster management. This type of approach emphasizes the activities and techniques that a technical team can implement to assess and reduce vulnerability [33].

The second is the social-constructivist framework, which focuses on human vulnerability [40]. In this framework, the social approach to vulnerability, both individual and collective, is a crucial dimension to study vulnerability to climate change, where social, economic, and institutional factors, in addition to biophysical ones, are taken into account [1,66]. In this sense, vulnerability is always linked to a specific hazard or set of hazards, which creates a close link between vulnerability and hazard [66].

The third is the IPCC's Fourth Assessment Report (AR4) framework, where exposure is considered an external dimension of vulnerability, and sensitivity and adaptive capacity as internal dimensions [40]. In the AR4, the IPCC defined vulnerability as the "[…] degree to which a system is susceptible and cannot cope with the adverse effects of climate change, [… which is in] function of the character, magnitude and rate of change and climatic variation to which a system is exposed, its sensitivity and its adaptive capacity" ([58]: 883). Sensitivity is understood as "[…] the degree to which a system is affected, adversely or beneficially, by climate variability or change" (Ibid: 881); while adaptive capacity is defined as "[…] the capacity of a system to adjust to climate change, to moderate potential damage, take advantage of opportunities or face the consequences" (Ibid: 869). However, the report does not define the concepts of exposure and risk. In summary, for AR4 the vulnerability is determined from the following equation:

AR4: Vulnerability = f (exposure, sensitivity, adaptive capacity)

However, today there is a fourth framework, from the IPCC's Fifth Assessment Report (AR5). In the AR5, vulnerability was redefined as "[…] the propensity or predisposition to be negatively affected" ([59]: 1775), being a function of sensitivity and adaptive capacity. In this report, sensitivity is defined the same way as in AR4, with the difference that, in addition to systems, species can also be affected; and adaptive capacity also includes institutions, humans, and other organisms.

In this new approach, vulnerability remains an element of risk. Risk is defined as the "[…] potential consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values, […] it is the result of the interaction of vulnerability, exposure, and hazard" ([59]: 1772). In this sense, the exposure refers to "the presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure or economic, social or cultural assets in places and environments that could be negatively affected" (Ibid: 1765). Thus, the equation that determines this new approach is:

AR5: Risk = f (hazard, exposure, vulnerability [f (sensitivity, adaptative capacity)])

Risk is a social construction derived from the production and reproduction of conditions of vulnerability and inequality [41,65]. Therefore, when "risks reach a certain level that is itself socially determined" ([41]: 21), they are considered disasters, which are historically constructed and differentially experienced. Therefore, what causes a disaster is the combination of a hazard and an exposed, vulnerable, and poorly prepared population or community [3]. For this reason, studies on disasters must analyze not only biophysical processes but also, and above all, the socioeconomic conditions in which they occur [41].

The integration of cities in the framework of the global climate agenda has been recent. In the AR4 (2007), the issue was tangentially tackled in Working Group (WG) II in a subsection entitled *Human settlement,* in chapter 7. It was not until 2014, in the AR5, that the importance of cities was recognized as part of the urban agenda in climate adaptation and mitigation. In AR5, a chapter entitled *Urban Areas* was included in the WG II on adaptation, and another entitled *Human Settlements, Infrastructure and Spatial Planning* in the WG III on mitigation.

In qualitative terms, the transition of the conceptual framework from AR4 to AR5 implied a shift from a predominantly biophysical approach to a more comprehensive one, in which the importance of other elements (beyond merely climatic ones, such as governance, social organization, teleconnections or cultural aspects) is recognized [59,74]. Despites approaches to vulnerability and disaster risk management advancing along separate routes, their interaction is unavoidable [3,4,38,82]. New studies would have to link both –vulnerability and disaster risk management agendas–, ground them to the local and urban level while progressing in the measurement and monitoring of climate risks and the actions proposed and executed to reduce those risks.

2.2. State of the art of the measurement of "vulnerability" and "risk"

Although the concepts of vulnerability and risk have evolved in the climate literature [57], it is important to identify if this has been translated into tools for measuring such phenomena. To find out the state of the art of vulnerability and risk indices, a Google search was carried out between January 16–30, 2020 and January 21–23, 2021, with the keywords "vulnerability/risk + index + climate change + urban" (in English and Spanish).[1]

The Google search allowed identifying both indexed literature in international journals, as well as gray literature or reports that are not indexed. All the results were reviewed, until reaching a saturation point. This saturation point occurred when the results showed repeated pages as well as pages that were not related to the search. For both searches

[1] Much of the international literature and indexed journals are in English (hence the importance of searching for the keywords in English). However, given that it was important to recognize the indicators and indices on vulnerability and risk to climate change in Mexico, the same search was made in Spanish. Furthermore, Spanish also allows the inclusion of literature from other countries in Latin America, being the dominant language in the region.

–English and Spanish– this saturation point was reached around page 8 to 10. The search yielded a total of 29 vulnerability indices and 18 risk indices (Table 1). An analysis of the indices was carried out, reviewing what they measure and their conceptual frameworks.

The 47 indices were classified according to the conceptual framework used (the one proposed by the IPCC in AR4, that related to AR5, or other). The classification of the indices in terms of their conceptual framework is given, in the first instance, in their definition of vulnerability and/or risk, but also in the indicators used. In this sense, although some of the indices use the IPCC definition, their indicators are not consistent with this framework; in this case, they would be classified as "other" framework. In turn, each of the three conceptual framework classifications was subdivided into the indices that use climatic indicators with respect to a baseline, a future scenario with projections, and those that do not take climatic indicators or variables into account.

The search yielded both vulnerability and risk indices in which the indicators used are not clear or transparent, meaning that they simply mention the categories or general themes considered; these indices are in the category "not clear or not transparent indicators".

From Table 1, it can be seen that, on the one hand, the vulnerability indices have been mostly based on the IPCC's AR4 conceptual framework or on a different one, and they exist both, for a baseline and for future scenarios. On the other hand, the risk indices have been developed recently, the majority taking different frameworks than the IPCC as a starting point. Finally, it should be noted that the opacity of some of the indices not only obscures what is evaluated by the users of the index, but also does not allow the evaluations to be adjusted to specific contexts or changing realities. Therefore, these opaque indices cannot promote social participation and the co-production of knowledge and solutions.

For the specific case of Mexico, five vulnerability indices were found: three of them under the AR4 framework and two with a different one. Of these five vulnerability indices, only three consider measurement at the urban level. However, to date, there are no urban risk indices for climate change in Mexico.

In summary, there are important but limited efforts to measure vulnerability to climate change at the urban scale. When available, studies do not usually make their measurement tools transparent, having opaque methodologies that do not indicate what was measured and how. This situation is doubly endorsed for the Mexican case where, in terms of risk, robust indicator systems that contribute to disaster risk management have not been implemented.

Faced with this panorama, we propose a toolbox that allows the measurement process to be transparent, rendering the index adaptable to the specificities of each case. Other future evaluations may enrich the toolbox with other indicators, as it is an instrument in permanent evolution. To show how the toolbox works, the URICC is applied to the Mexico City case.

3. Materials and methods

3.1. Mexico city as a case study

The most populated urban settlement in Mexico is its capital, Mexico City, which has over 9.2 million inhabitants [53]. For this paper, the 16 municipalities of central Mexico City are taken as a case study (see Fig. 3). More than half of the territory of Mexico City (59%) is Conservation Land. The Conservation Land is found mainly in the municipalities of Xochimilco, Tlalpan, and Milpa Alta (south of Mexico City); and to a lesser extent in Cuajimalpa, Tlahuac, Magdalena Contreras, Alvaro Obregón, Gustavo A. Madero and Iztapalapa. The municipalities with the largest population are Iztapalapa (1.83 million) and Gustavo A. Madero (1.17 million) [53]. The municipalities with the highest percentage of the population living in poverty are Milpa Alta (49.2%), Xochimilco (40.5%), Tlahuac (39.2%), Iztapalapa (35%) and Magdalena Contreras (32.6%) [20], while the municipalities with the lowest percentage of the population living in poverty are Benito Juarez (5%) and Miguel Hidalgo (7.1%) (Ibid).

The population in Mexico City is mainly urban and dedicated to tertiary activities. Mexico City has the highest population density in the country (6006 inhabitants/km^2 if the total area is taken into account and 14645 inhabitants/km[2] if only the urbanized area is considered; [52]), and has inequality figures higher than those of the national average generating "two cities" within the entity: in 2018, 10% of the richest population accumulated 60% of income and the poorest 40% accumulated only the 8% of income [36].

Mexico City is in the Valley of Mexico Basin, where the lowest and flattest part is established in the old bed of a lake. It has a tropical mountain climate, where the central-southern part of the city is temperate, the north-eastern part is dry steppe, and the central-eastern part is semi-arid [71]. The average annual precipitation in the dry region is 600 mm, and in the humid temperate part is 1200 mm [52], while the average temperature varies between 18 °C and 11 °C [50]. These characteristics and biophysical conditions of Mexico City are determining factors for the main threats identified by climate change scenarios: torrential rains, decreased precipitation, increased temperature and the urban heat island, cold shocks (especially in higher altitude areas), and gales [64,78]. The main impacts of these threats materialize in floods, mass movements, heat waves, water stress, and droughts, damage to infrastructure and buildings, as well as effects on livelihoods, health, and the economy.

The climate change scenarios for Mexico on the near horizon (2015–2039) project annual temperatures that exceed 2 °C in the north of the country and between 1 °C and 1.5 °C in the rest of the territory, as well as a decrease in precipitation between 10 and 20% [48]. Scenarios for the case of Mexico City in the near horizon (2015–2039), with different models (MPI, HADGEM2, GFDL, and CNRMCM5), show a clear increase in temperature in all municipalities throughout the year, with the warm months (March to October) predicted to become warmer and the cold months (November to February) less cold [26]. In the case of precipitation, the changes in patterns are not so evident and vary according to the model used, being for some the dry season (November to May) getting drier and for others less dry; and the rainy season (June to October), in general, less rainy (Ibid).

In Mexico, the federal, state and municipal levels of government share the responsibility to legislate and develop public policies on urban planning, risk management, and climate change [3]. Specifically, Mexico City has developed some local public policies related to climate change. To mention a few, in 2004, the *Local Strategy for Climate Action* was published; in 2008, the first *Climate Action Program 2008–2012* was promulgated; in 2011, the *Law on Mitigation and Adaptation to Climate Change and Sustainable Development* was published; in 2014, the second *Local Climate Action Strategy (2014–2020)* was implemented, as well as the second *Climate Action Program (2014–2020)*; and in 2015, the creation of the *Environmental Fund for Climate Change* was approved. Since the end of 2019, the *Local Strategy for Climate Action 2021–2050* and the *Climate Action Program of Mexico City 2021–2030* have been prepared.

3.2. Construction of a toolbox with indicators to assess vulnerability and risk to climate change at an urban scale, and the URICC for Mexico city

To build the toolbox we included all the indicators that we reviewed in the indices presented in Table 1, and we complemented it with important topics in terms of climate risk in the context of Latin America. In this sense, the toolbox incorporates what has been measured in terms of vulnerability and risk to climate change, both nationally and internationally, by the 47 indices analyzed in the review of the state of the art

[2] The weight given to each dimension should ideally reflect the most pressing socio-ecological challenges in the city where it is applied. Attribution of weight to the dimensions could therefore be a participatory exercise involving local stakeholders (see for example [67].

Table 1
State of the art of the revised indices for climate change vulnerability and risk.

Vulnerability/Risk	Conceptual framework	Type of indicators	Index name	Country or city where it is tested/developed	Source
Vulnerability	AR4	Baseline	Heat Vulnerability Index	Australia	[108]
			Urban Vulnerability Index	Beijing	[115]
			Climate Vulnerability Index	Malawi and Mali	[39]
			Climate change vulnerability assessment for Can Tho city by a set of indicators	Can Tho, Vietnam	[102]
			Manual for gender-responsive climate change vulnerability assessments	Indonesia	[101]
			Village Vulnerability and climate risk index Nusa Tenggara Timur	Nusa Tenggara Timur, Indonesia	[7]
			Climate change vulnerability assessment of urban informal settlers in Nepal, a least developed country	Nepal	[42]
			Climate change vulnerability in urban slum communities: Investigating household adaptation and decision-making capacity in the Indian Himalaya	Indian Himalaya Region	[85]
		Future scenario	National Atlas of Vulnerability to Climate Change	Mexico	[49]
			Climate Action Program of Mexico City	Mexico City	[18]
			Climate Change Vulnerability Index	Mexico	[76]
			University of Notre Dame Global Adaptation Index	Indiana, USA	[16]
			Assessing Vulnerability to Climate Change: An Approach Illustrated through Large Urban Scale Adaptation (Urb-ADAPT)	Ireland	[87]
	AR5	Baseline	Indicator-based Vulnerability to Climate Change Assessment for European cities	European cities	[100]
	Other	Baseline	Climate Change Vulnerability Index for mall craft harbours	Greece	[68]
			Heat Vulnerability Index	Chicago, USA	[112]
		Future scenario	Physical Vulnerability to Climate Change Index	Developed by France and tested worldwide	[17]
			Vulnerability and Adaptation Assessment	–	[111]
			Climate Vulnerability Index of Mexican Cities	Mexico	[47]
			A flood vulnerability index for coastal cities and its use in assessing climate change impacts	Developed by The Netherlands and tested in different coastal cities worldwide	[5]
		No climatic variables	Analysis of population vulnerability at hazard areas InVU + InVH	Santa Maria, Brazil	[103]
			Climate Change and Flood Risk Assessment	Jalisco, Mexico	[44]
			Developing a Climate-Induced Social Vulnerability Index for Urban Areas: A Case Study of East Tennessee	Tennessee, USA	[13]
	Not clear or not transparent indicators		Vulnerability Index to climate change	Latin America	[10]
			Climate Change Vulnerability Index	Global	[109]
			Climate Vulnerability Index	Australia	[22]
			Urban Flood Vulnerability Index	Guwahati, India	[95]
			Development of a climate change risk and vulnerability assessment tool for urban areas: Green and Blue Space Adaptation for Urban Areas and Eco Towns	UK	[14]
			Vulnerability and Adaptation in the Ukrainian Cities under Climate Change	Ukraine	[98]
Risk	AR5	Baseline	World Risk Report	Developed by Germany and tested worldwide	[79]
			Mountain specific multi-hazard risk management framework (MSMRMF)	Indian Himalayan Region	[96]
		Future scenario	Climate risk index for Italy	Italy	[80]
	Other	Baseline	Global Climate Risk Index	Developed by Germany and tested worldwide	[34]
			Disaster Risk Index	Developed by Switzerland and tested worldwide	[89]
			Natural Disaster Hotspots: A Global Risk Analysis	Developed by New York, USA, and tested worldwide	[30]
			Natural Hazard Risk Index for Megacities	Developed by Germany and tested worldwide	[32]
			Global Risk Index 2019	Developed by UK and tested worldwide	[11]
			Urban-Hazard Risk Analysis: Mapping of Heat-Related Risks in the Elderly in Major Italian Cities (HERI)	Italy	[77]
			Zoning and weighting in urban heat island vulnerability and risk mapping in Helsinki, Finland	Helsinki, Finland	[91]
		Future scenario	Urban Risk Assessment	Developed by Canada & USA, and tested worldwide	[29]
			Global ranking of port cities with high exposure to climate extremes	Developed by UK & France, and tested worldwide	[45]
			A Global Urban Risk Index	Global	[9]
			The Global Risks Report	Global	[110]
			Heat stress risk and vulnerability under climate change in Durban metropolitan, South Africa	Durban metropolitan, South Africa	[63]
	Not clear or not transparent indicators		Index-based assessment of perceived climate risk and vulnerability for the urban cluster	China	[99]
				Spain	[104]

(continued on next page)

Table 1 (*continued*)

Vulnerability/Risk	Conceptual framework	Type of indicators	Index name	Country or city where it is tested/developed	Source
			Evaluación de la vulnerabilidad y riesgo de los municipios vascos ante el cambio climático		
			The Climate and Ocean Risk Vulnerability Index	Developed by USA, and tested in Caribbean and African cities	[114]

previously described. However, the review of vulnerability and climate risk indices primarily from the Global North may overlook dimensions that are characteristic of the Global South. To avoid this, we conducted a literature search on the main causes of risk in Latin American cities, which helped us complement the list of indicators with other pertinent themes. The literature reviewed for this purpose [6,59,72,78,94] discusses aspects such as sustainability and climate change, the unequal production of space, environmental (in)justice, poverty and informality. Thus, 33 relevant subdimensions in terms of vulnerability and climate risk were incorporated, with a total of 41 possible indicators and their respective sources of information.

In total, 1027 indicators were collected: 90 for hazard, 177 for exposure, 187 for sensitivity, 226 for adaptive capacities, 157 for vulnerability, 90 for risk, 6 for shocks, 6 for resilience, 47 combined in the various categories, and 41 relevant for Latin America (see Annex A in supplementary material). The subdimensions and related indicators were grouped to facilitate the visualization of the main themes in each risk category (Fig. 1).

The toolbox is intended to function as "an evaluation guide that must be interpreted sensitively according to the specificities of each case" ([24]: 115-116). Careful adaptation of the toolbox to different socio-ecological contexts is necessary to avoid a global standardization of measurements tools that may affect their applicability locally [24,35]. Therefore, the toolbox constitutes an instrument in constant construction that can evolve as new measurement tools are developed, which is important for the process of knowledge co-production and for the coupling of various analytical methods [24].

The extensive toolbox (Annex A in supplementary material) can be used to generate robust measures of climate risk and vulnerability with an interdisciplinary approach, which can ideally become transdisciplinary if actors outside academia are involved in its implementation. Its versatility allows the user to choose the form that best suits their interests to measure vulnerability and risk to climate change, which means that the results of the use of the toolbox will depend on the quality of the evaluation process and the use given to it [25]. This implies a sense of responsibility and ethics of whoever uses the tool with a

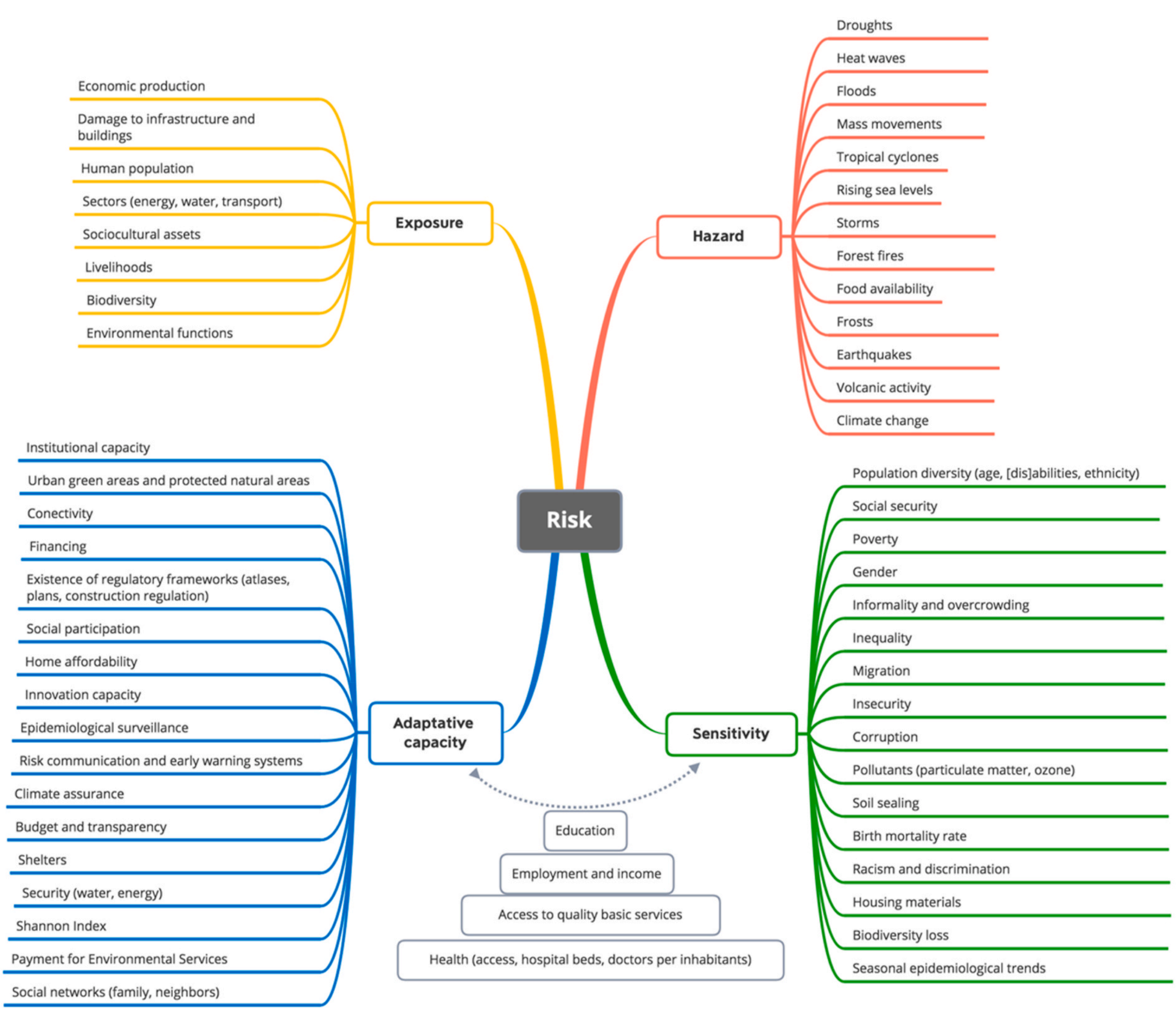

Fig. 1. Relevant subdimensions and indicators to assess climate change risk.

view to reduce climate risks at the local level.

In this sense, the user can choose the tools to assess vulnerability or risk at a given moment (historical memory or actual risk) or to project future scenarios; the user can take tools in isolation or group them in an index with a biophysical, social, economic approach or, in the best of cases, combine tools with a more comprehensive approach. In short, the toolbox can be as powerful as the use given to it, be it by a single user or multiple users who could ideally co-generate knowledge and provide more robust and complex solutions.

To show the functioning of the toolbox, we apply it to the case of Mexico City by selecting a list of indicators pertinent to our case study. The selection of these criteria for Mexico City responded to the need to generate a comprehensive index that would cover the ecological, socio-cultural, and economic dimensions of risk in the face of climate change. For the construction of the URICC, we followed a series of criteria to select a group of indicators from the 1027 available in the toolbox. We describe these selection criteria below:

- The first selection criteria responded to those subdimensions and indicators that were repeated in at least two of the state-of-the-art indices. We considered that their repetition reflects a consensus on their relevance.
- As a second criterion, we verified that the selected subdimensions and indicators were not redundant (in order not to measure poverty or illiteracy as sensitivity, and economic income or literacy as adaptive capacity; to give an example).
- The third criterion accounted for those significant indicators for the 16 municipalities of Mexico City corresponding to an inner city (which excluded subdimensions or indicators related to coastal cities, for example) and a central city (which excluded subdimensions or indicators that account for the interdependence of the central city with surrounding regions).
- The fourth criterion was based on the availability of data because, despite the importance of continuously generate new information on risk, this work is limited to proposing a preliminary index of urban risk based on secondary data.

In summary, the chosen indicators responded to a consensus about their importance in international literature, their relevance for Mexico City, and the availability of data. The indicators selected are presented in Fig. 2. We decided to choose three categories in each of the four risk subdimensions. This way, the index brings together twelve categories in a series of clearly described indicators, in a robust way and appropriate to the context of Mexico City, which allows it to be a clear, relevant, and verifiable index [105].

To recognize the importance of each one of the risk subdimensions, we decided to give the same weight to all subdimensions and categories, thus having 50% of the assessment correspond to the biophysical aspects (25% exposure and 25% hazard) and the other 50% to socioeconomic elements (25% sensitivity and 25% adaptive capacity).[2] Likewise, each subdimension of risk was valued with 25%, and each indicator represented 25% within its own subdimension.

We evaluated the URICC for 2015 as a baseline and for 2030 at the municipal level. Each indicator was estimated for all municipalities. The URICC was evaluated with two different models: 1) the first model (model 1) assesses the progress or setback regarding the national commitment to reduce by 2030 the vulnerability of municipalities by 50% [43]; 2) the second model (model 2) compares the climate-related risk municipalities will face by 2030. The data sources for 2015, the projections for 2030, and the estimates for model 1 and model 2 are shown in Table 2. Model 1 shows the percentage of setback with respect to the goal of reducing half of the municipalities' vulnerability by 2030. On the other hand, model 2 shows a comparison of risk between municipalities on a scale from zero (lower risk) to ten (higher risk).

An analysis was simultaneously carried out at the Basic Geostatistical Areas level –territorial extension that corresponds to the subdivision of municipal areas, and constitutes the basic unit of the National Geostatistical Framework– with the available data at this scale (2010). This analysis allowed to identify the polygons with the highest risk within each municipality and that require priority attention.

To develop the maps presented in section 4 (Results), we used QGis. The tables in Excel with the results of model 1 and 2, as well as with the indicators at the Basic Geostatistical Areas level, were exported in csv format. The mapping was carried out with the "graduated" function and the classes in equal count for the population density and housing density; and equal interval for population from 0 to 14 years old, 65 and over, and in indigenous census households.

4. Results

Our results show that all of Mexico City's municipalities are prone to climate risks. However, the magnitude of risk differs according to the model used (see Table 4). In model 1, the percentage of decline with respect to the goal of reducing vulnerability by 50% by 2030, varies from 9% in Coyoacán to 18% in Milpa Alta (in Fig. 3, municipalities in red showed a setback around the national goal of reducing half of the municipalities' vulnerability by 2030). In model 2, the municipalities with the lowest risk are Milpa Alta and La Magdalena Contreras, and the one with the highest risk is Iztapalapa. Thus, while in model 1, Milpa Alta is the municipality that will present a greater setback compared to the national goal by 2030, in model 2, it is the municipality with the lowest risk compared to the others.

When analyzing isolated indicators at the Basic Geostatistical Areas level, we observe that the most exposed population (population per square kilometer per Basic Geostatistical Areas level; Fig. 4) is located in the central area of Coyoacán (in Santo Domingo), in the southern area Iztapalapa and in the southern area of Iztacalco, in the northern area of Cuauhtémoc, in the western area of Azcapotzalco, in the area of the Álvaro Obregón ravines and in the northeast of Gustavo A. Madero. Likewise, the exposed homes (homes per square kilometer per Basic Geostatistical Areas level; Fig. 4) coincides with the areas of the exposed population, although Benito Juárez is added, one of the municipalities with the highest increase in vertical constructions in recent years [25].

Regarding sensitivity (Fig. 5), children (0–14 years old) are concentrated in the central-eastern area of Xochimilco, in the central area of Coyoacán, in the upper area of Cuajimalpa, and in the ravines of Álvaro Obregón. Likewise, the elderly (65 years and over) are concentrated in the central area of Coyoacán and in the area of the Álvaro Obregón ravines, in the central area of Benito Juárez, Cuauhtémoc and Iztapalapa. On the other hand, the indigenous population is living mainly in the central-eastern zone of Xochimilco, the central zone of Coyoacán, and the border between Iztapalapa and Tláhuac. Finally, the areas with the largest population living in poverty (70–100% of the population living in poverty) are in the central part of Xochimilco, in numerous areas of Iztapalapa with emphasis on its border with Tláhuac, central Tláhuac, as well as in the northern part of Gustavo A. Madero.

Iztapalapa is the municipality with the highest risk to climate change 2015–2030 compared to other municipalities; but this risk is unequally distributed within the municipality: the areas of greatest risk in Iztapalapa and where the greatest attention should be focused is in the southern area that limits this municipality with Tláhuac (high exposure of population and dwellings, high sensitivity of the indigenous population and of the population living in poverty). Coyoacán, although obtaining an intermediate risk in model 2, displays polygons with high risk when analyzed at Basic Geostatistical Areas level, specifically the Santo Domingo neighborhood (high exposure of population and

[3] ICI-CLIMA (Climate-Environmental Local Institutional Capacity Index) is an index developed by Delgado [27] that offers an "assessment of the existing climate-environmental local capacities in the Metropolitan Area of the Valley of Mexico"[27].

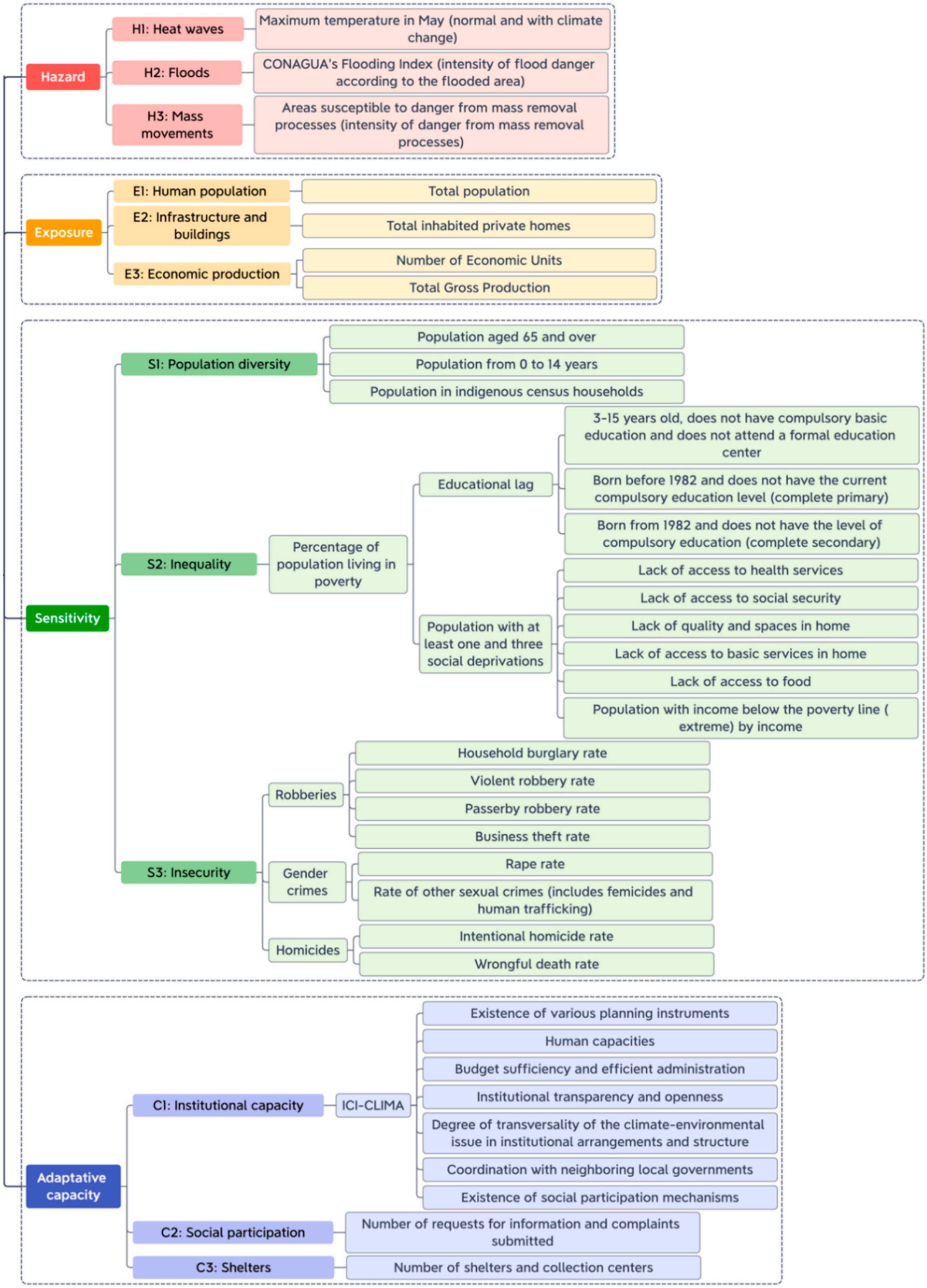

Fig. 2. Subdimensions and indicators that make up the URICC for Mexico City.[3]

Table 2
Data for baseline (2015), future estimates (2030), and model 1 and model 2 estimates.

Indicator	Data for baseline (2015)	Data for future estimate (2030)	Model 1 and Model 2
Heat waves (H1)	Maximum temperatures in the month of May (warmest month) 1950–2000 were recorded from the WorldClim database by municipality.	Climate change scenarios for the near future (2015–2039) were modeled with four different general circulation models (CNRMCM5, GFDL_CM3, HADGEM2_ES, and MPI_ESM_LR), obtaining a projection of the change (1950–200 and 2015–2039) in the maximum temperature in May for the 16 municipalities.	The difference of the maximum temperature from the baseline and the maximum temperature estimated with the climate change scenarios for each municipality was calculated. It was considered that, as the Paris Agreement establishes, the goal is to limit the temperature increase to 1.5 °C. For model 1, the temperature difference of each municipality was ranked according to a scale in which the values change every 0.3 °C of increase in temperature (the factor value used was then 0.3222), and the temperature increase was translated to the URICC scale (Table 3). For model 2, the temperature difference was divided by the largest temperature difference between the municipalities.
Floods (H2)	SGIRPC [97].	The flood data for 2015 is based on the flood index, which depends on multiple meteorological, hydrological and human factors. Therefore, making the projection to 2030 is a complex process, which transcends the objective of this work. By 2030, then, it was assumed that the flood index would remain, not only because of the difficulty of projecting the index, but significant changes in urban infrastructure cannot be assumed in the short term.	For model 1, given that the projections were not made due to the complexity of estimating future flood behavior, a value of 0.5 (neutral value, neither advance nor setback) was assigned to all municipalities. For model 2, the following scale was followed for the URICC: 0–25% of floodable area = 1, 0–100% of floodable area = 5, 100% of floodable area = 10.
Mass movements (H3)	SGIRPC [97].	The same data were maintained for 2030, because they depend on many factors, including informality processes.	For model 1, given that the projections were not made due to the complexity of estimating future behaviors of mass movements, a value of 0.5 (neutral value, neither advance nor setback) was assigned to all municipalities. For model 2, the following scale was followed for the URICC: very low hazard = 1, very low to low hazard = 2, very low to medium hazard = 3, very low to high hazard = 4, very low to very high hazard = 5.
Human population (E1)	INEGI [51].	The CONAPO projection (2010) was adjusted with the population data from the Intercensal Survey [51], and with the annual growth rate expected by municipality from 2015 to 2030 [19]; highlights that the estimates for 2030 are slightly lower than those originally projected by CONAPO.	For model 1, the percentage of increase or reduction of the population by municipality 2015–2030 was calculated, this in relation to the advance/setback with respect to the goal of reducing people's vulnerability by 50%, and it was translated to the URICC rating scale (Table 3). For model 2, the population projected to 2030 of each municipality was divided by the municipality with the largest population projected to 2030.
Infrastructure and buildings (E2)	INEGI [51].	It was calculated following the trend of its growth observed from 1990 to 2015 with respect to the population [15], being that the annual average housing rate increases 1.2% over the population. So, it is estimated that, if for the 2015–2030 period the annual population growth	For model 1, the percentage of increase or reduction of housing rate by municipality 2015–2030 was calculated, this in relation to the advance/setback with respect to the goal of reducing vulnerability by 50%, and it was translated to the URICC rating scale (Table 3).

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Table 2 (*continued*)

Indicator	Data for baseline (2015)	Data for future estimate (2030)	Model 1 and Model 2
		rate will be −0.3%, the average annual growth rate for housing will be 0.9%, and it is also assumed that due to the COVID-19 pandemic in 2020 there will be no an increase in the housing growth rate, so 14 years instead of 15 were considered for the 2015–2030 period.	For model 2, the housing rate projected to 2030 in each municipality was divided by the municipality with the largest housing rate projected to 2030.
Economic production (E3)	Estimated with the Economic Censuses 2013 and 2018 [54].	To project the Total Gross Production (TGP), data from the Economic Censuses 2008, 2013 and 2018 [54] were used, a decrease of the TGP of −0.3% was estimated for 2019 [113], a reduction of −6.8% for 2020 (according to the city's Undersecretariat for Economic Development [69], a growth rate of 3% for 2021 [113], and for 2022–2030 an increase of 3.4% per year [84]. To calculate the Economic Units (EU) in 2030, it was observed that the growth rate from 2008 to 2018 was 20% and that of the TGP was 83% (that is, for every 1% of the EU the TGP increases 4.1%), while for the period 2019–2030, the projected TGP would increase 30%, therefore, the EU would do so at a rate of 7.2%. However, due to the pandemic 85,000 establishments have been reported in danger of bankruptcy in Mexico City [69], so subtracting this figure, it is calculated that the EU exchange rate from 2018 to 2019–2030 will be −13%, a percentage that was subtracted from the EU in 2018.	For model 1, the percentage of increase or reduction of the EU and the TGP by municipality 2015–2030 was calculated, this in relation to the advance/setback with respect to the goal of reducing its vulnerability by 50%, and it was translated to the URICC rating scale (Table 3). For model 2, the EU and TGP projected to 2030 of each municipality were divided by the municipality with the highest EU and TGP, respectively, projected to 2030.
Population diversity (S1)	INEGI [51].	It was estimated that the population aged 65 years and over will represent 15% of the total population, while the population aged 0–14 will be 19%, according to the report by CESCDMX [15]. The population in indigenous census households was estimated based on the percentage it represented with respect to the total population in 2010.	For model 1, the percentage of increase or reduction of the population in indigenous census households, population over 65 years and 0–14 years by municipality 2015–2030 was calculated, in relation to the advance/setback with respect to the goal of reducing vulnerability 50%, and it was translated to the URICC rating scale (Table 3). For model 2, the population in indigenous census households, population over 65 years and 0–14 years projected to 2030 of each municipality were divided by the municipality with the largest population in indigenous census households, population over 65 years and 0–14 years, respectively, projected to 2030.
Inequality (S2)	CONEVAL [20].	The correlation with the annual TGP behavior was assumed and a poverty projection was made for 2016–2018. For the latter, the following calculations were made: (1) TGP deflated at 2013 prices considering an inflation effect of 27.35% between January 2013 and December 2018, according to the National Consumer Price Index of INEGI [55]; (2) percentage of real depreciation of TGP 2013–2018; (3) percentage of poverty 2013–2018 based on the fact that poverty decreases −0.19% for each increase of 1% of TGP, according to EVALUA [36]; and finally, (4) poverty for 2016–2018. Subsequently, for 2019–2030 it was estimated: (1) TGP	For model 1, the percentage of increase or reduction of poverty by municipality 2015–2030 was calculated, this in relation to the advance/setback with respect to the goal of reducing vulnerability 50%, and it was translated into the URICC rating scale (Table 3). For model 2, the poverty projected to 2030 of each municipality was divided by the municipality with the highest poverty projected to 2030.

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Table 2 (*continued*)

Indicator	Data for baseline (2015)	Data for future estimate (2030)	Model 1 and Model 2
		deflated at 2019 prices with an inflation effect of 2.74% in 2019 and for the period 2020–2030 assuming an annual inflation of 3.84% derived from the average value of inflation in January from 2010 to December 2019, based on the National Consumer Price Index of INEGI (nd); (2) percentage of real depreciation of the TGP 2019–2030, and (3) percentage of poverty 2019–2030. And, to obtain the percentage of the population living in poverty by 2030, the 2015 poverty calculated by CONEVAL was added, plus the estimated 2016–2018 poverty, plus the estimated 2019–2030 poverty.	
Insecurity (S3)	OCM [83].	Data from the Citizen Observatory of Mexico City for 2018 were used, these being the most recent. These data were not projected due to the difficulty of estimating future levels of violence, since it has been shown that there is no direct correlation between poverty and/or unemployment with crime [81,90]. Diverse factors influence criminal levels, from social backwardness and poverty to population density, diversity of age groups, school dropouts, urban infrastructure and equipment, and even family disintegration.	For model 1, the percentage of increase or reduction of insecurity by municipality 2016–2018 was calculated, this in relation to the advance/setback with respect to the goal of reducing vulnerability 50%, and it was translated into the URICC rating scale (Table 3). For model 2, the insecurity in 2018 of each municipality was divided by the municipality with the highest insecurity in 2018.
ICI-CLIMA (C1)	PCTU [88].	The 2019 data were used, as they are only available for this year. It is noted that institutional capacities change over time, practically with the arrival of each new government, given that, on multiple occasions, they not only replace the pre-existing teams, but also lack previous reports and documents.	For model 1, given that the projections were not made due to the complexity of estimating future institutional capacities, a value of 0.5 (neutral value, neither advance nor setback) was assigned to all municipalities. For model 2, the ICI-CLIMA value of each municipality was divided by 3, as ICI-CLIMA scale value ranges between 0 (absence of capacities) and 3 (robust capacities).[a]
Number of requests for information and complaints submitted (C2)	InfoDf [56] and PAOT [86].	The 2019 data were used, as they are only available for this year. However, the rates were calculated with respect to the estimated population as of 2030.	For model 1, the percentage of increase or reduction in the rate of complaints and requests for information by municipality 2019 (according to the population 2015–2030) was calculated, in relation to the advance/setback with respect to the goal of reducing 50% vulnerability, and was translated into the URICC rating scale (Table 3). For model 2, the rate of complaints and projected requests for each municipality was divided by the municipality with the highest rate of complaints and requests, respectively, projected to 2030.
Number of shelters and collection centers (C3)	SGIRPC [97].	The 2019 data were used, as they are only available for this year. However, the rates were calculated with respect to the estimated population as of 2030.	For model 1, the percentage of increase or decrease in the rate of shelters and collection centers by municipality 2019 (according to the population 2015–2030) was calculated, in relation to the advance/setback with respect to the goal of reducing vulnerability by 50%, and was translated into the URICC rating scale (Table 3). For model 2, the

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Table 2 (*continued*)

Indicator	Data for baseline (2015)	Data for future estimate (2030)	Model 1 and Model 2
			rate of shelters and collection centers projected for each municipality was divided by the municipality with the highest rate of shelters and collection centers, respectively, projected to 2030.

[a] For more details see: https://transformacionurbana.mx/es/proyectos/interfaz_cp/diagnostico-zmvm/cdmx/

Table 3
Rating scale for model 1.

Percentage of advance (%)	Translation to IRUCC
80 to 100	0.10 to 0
60 to 79.99	0.20 to 0.11
40 to 59.99	0.30 to 0.21
20 to 39.99	0.40 to 0.31
0 to 19.99	0.50 to 0.41
Percentage of setback (%)	**Translation to IRUCC**
−0 to-19.99	0.51 to 0.60
−20 to-39.99	0.61 to 0.70
−40 to-59.99	0.71 to 0.80
−60 to-79.99	0.81 to 0.90
−80 to-100	0.91 to 1.00

Table 4
Results of the URICC 2015–2030 for Mexico City in model 1 and in model 2.

Municipality	Model 1: percentage of decline with respect to the goal of reducing vulnerability by 50% (from 0 to 100%)	Model 2: risk comparison between municipalities (from 0 to 10)
Azcapotzalco	12.18	4
Coyoacán	9.39	4
Cuajimalpa de Morelos	14.77	4
Gustavo A. Madero	11.16	6
Iztacalco	14.01	4
Iztapalapa	13.17	8
La Magdalena Contreras	14.23	3
Milpa Alta	18.47	3
Álvaro Obregón	14.84	5
Tláhuac	15.79	4
Tlalpan	11.46	5
Xochimilco	15.27	5
Benito Juárez	12.93	4
Cuauhtémoc	14.73	5
Miguel Hidalgo	17.26	4
Venustiano Carranza	13.82	5

housing, high sensitivity of the child population, older adult and indigenous population).

5. Discussion

One important insight of our analysis is that different measurement methods yield different results. The results of model 1 and model 2 at the municipal level, and the isolated indicators at the Basic Geostatistical Areas level, differ in their identification of the municipalities presenting the highest risk. This divergence in results can be explained by the fact that the two models have different objectives: model 1 aims to recognize the advance or setback of the municipalities regarding the national commitment to reduce by 2030 the vulnerability of the municipalities by 50%, while model 2 aims to make a comparison between municipalities regarding the climate-related risk they will face by 2030. These results suggest that what is measured (selected indicators), how it is measured (objective and weighting), and at what scale it is done (state, municipal or local) is extremely important. For example, Das et al. [21], show that measuring vulnerability from the IPCC's AR4 framework and measuring risk from the IPCC's AR5 framework yield different results. For this reason, making the indicator systems methodologies transparent is a crucial matter to understand and take into account the context, focus, variables, and data sources. If policymakers are expected to use such indicator systems, making their construction transparent thus becomes a politics and policy issue [37].

The contrast between model 1 and model 2 at the municipal level, and the isolated indicators at the Basic Geostatistical Areas level, also suggests that interventions to reduce the risk of climate change should be studied at the finest possible spatial scale. De Moel et al. [23], for example, warn that small and micro-scale evaluations can directly support decision-making in a specific area. In the case of Mexico City, that is at the Basic Geostatistical Areas level. This scale is the one that shows the specific intervention points and allows to have contextualized measurements, which are blurred when weighing an index or when increasing the scale, say when doing it at the municipal or state level. The results at the Basic Geostatistical Areas level show that socioeconomic inequality is contrasting even at the local level. The intersection of social characteristics (population of the elderly, children, and indigenous people) with economic characteristics (poverty) in certain areas has a greater impact on climate risk and social vulnerability. Derived from this, designing policies to address risk would require an in-depth analysis of the causes of these socioeconomic conditions, which would need to be reviewed in the light of the history of such demarcations and the processes of migration and urban consolidation. Climate change aggravates those historical processes that have generated conditions of socioeconomic inequality [28,62].

Due to the lack of data at the municipal and Basic Geostatistical Areas level, relevant elements were discarded in the measurement of the URICC, for example, labor or housing informality, food poverty, corruption, housing materials, and social networks. The discussion on the availability of information in the literature on indicator systems is latent. Further research should tackle this data gap and produce localized data on these topics.

6. Conclusions

In this paper, we have presented a toolbox to measure urban risk to climate change. This toolbox addresses some of the major shortcomings of the current state of the art of urban risk indices. Firstly, by being transparent on the selection of indicators and measurement methods, our toolbox addresses the lack of transparency which is prevalent in the literature on risk indicators. By being explicit on the conceptual framework used, we aim to propose a framework to evaluate urban risk to climate change which can be shared across research efforts and thus contribute to more homogenous indices to assess risk in different cities. Our toolbox also has the potential to be used in transdisciplinary efforts, where civil society is involved in assessing risk and implementing adaptation interventions. We hope that its use can enhance processes of coproduction, across sectors of society, of policy-relevant knowledge (and actions) for locally coping with climate change risk.

In subsequent measurements, the URICC will need to be debated in a transdisciplinary working group that creatively integrates diverse specialists (in climate and economic modeling, in social and legal sciences, etcetera), as well as governmental, private sector, and, above all, civil

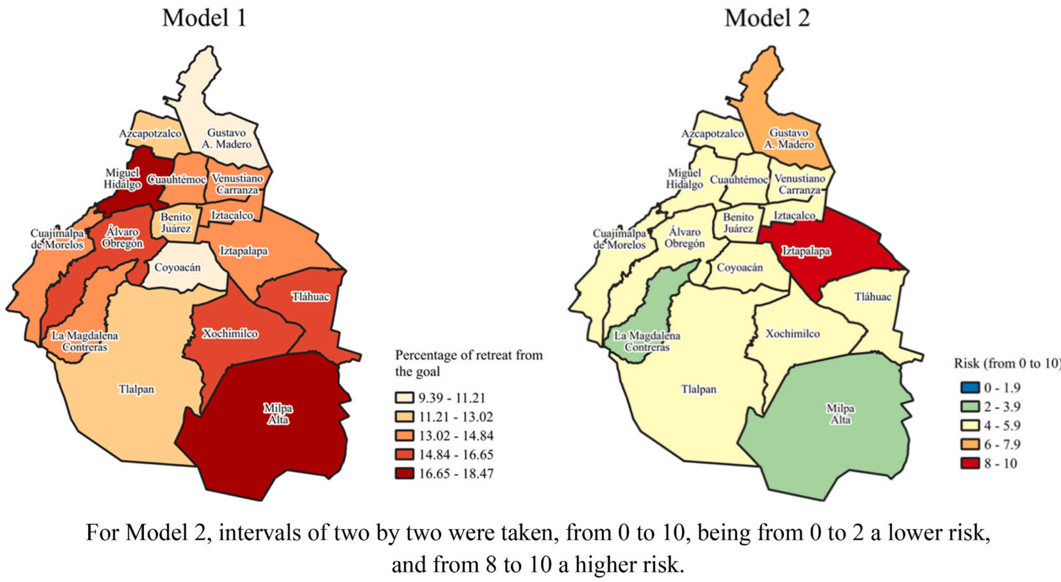

Fig. 3. Setback in relation to the 2030 national goal of halving the vulnerability of municipalities, 2015–2030 (model 1) and comparison of risk among the municipalities of Mexico City, 2015–2030 (model 2).

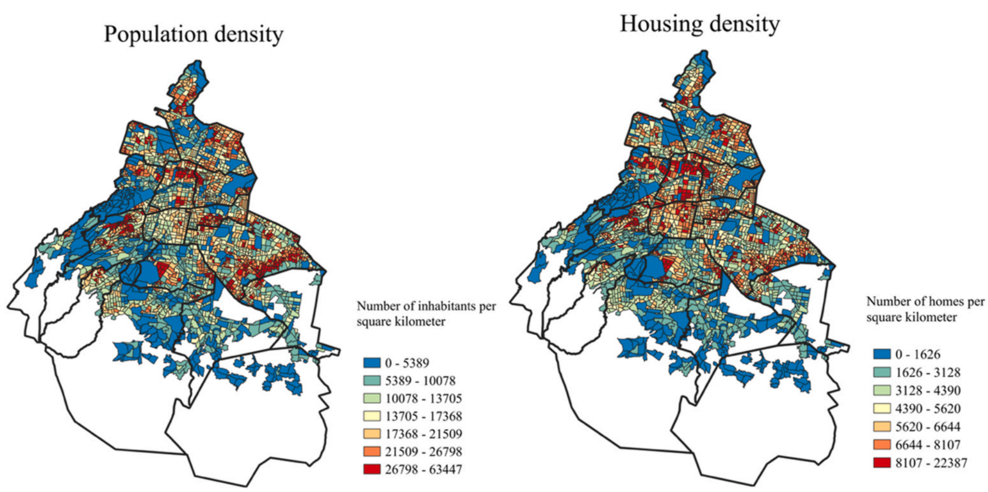

Fig. 4. Exposure indicators (population and housing density) at the Basic Geostatistical Areas level, 2010.

society. The co-production of knowledge, then, requires that scientific knowledge be an ally, at the same time that the figure of the expert is called into question, as scientific knowledge alone is insufficient. For tackling complex socio-environmental problems, "the contribution of multiple knowledge sources and capacities from different stakeholders spanning the science-policy-society interface" is needed ([31]: 886), to improve environmental decision-making and to make collective site-specific agreements for a place and a given time [107].

Finally, our toolbox emphasizes the importance of a holistic approach to adaptation which combines biophysical and socioeconomic dimensions. The conceptual evolution of vulnerability and risk from AR4 to AR5 in the IPCC represents a transition from a biophysical approach to a more comprehensive and of an interdisciplinary nature. The biophysical approach to the issue of climate change has emphasized action mainly around mitigation measures and hard adaptation interventions (through infrastructure or technological applications; [78]). This tend to put aside the socioeconomic asymmetries and prevailing cultural practices, even though risk is a social construction derived from the production and reproduction of conditions of vulnerability and inequality [1,41]. In this context, the advancement of other forms of adaptation, especially soft interventions (political or social actions; [78]), is undoubtedly desirable for the advancement of the aforementioned comprehensive approach, which is intended to be addressed from the conceptual transition from vulnerability to risk. Despite its importance, the conceptual framework evolution from vulnerability to risk is not yet reflected in the indicator systems, where an increase in the generation of risk indices is observed, but not as accelerated in comparison to the vulnerability indices.

In terms of public policies, the separation of vulnerability and risk is expressed in the lack of coordination of climate and civil protection policies, which in the case of Mexico tend to be reactive [2]. The case of Mexico City is not the exception in what specifically concerns the impacts of climate change, despite the fact that the urban resilience agenda was recently integrated into that of civil protection (which implies a shift in the conception of the latter: from reactive to an integrated disaster risk management; [2]). The articulation of the new strategy and its climate action plan could, however, be heading on the right path.

We hope to see the toolbox applied to other cities in Latin America. This will help explore its pertinence and the needs for local adjustments beyond the Mexican context. Indicator systems, as useful tools to

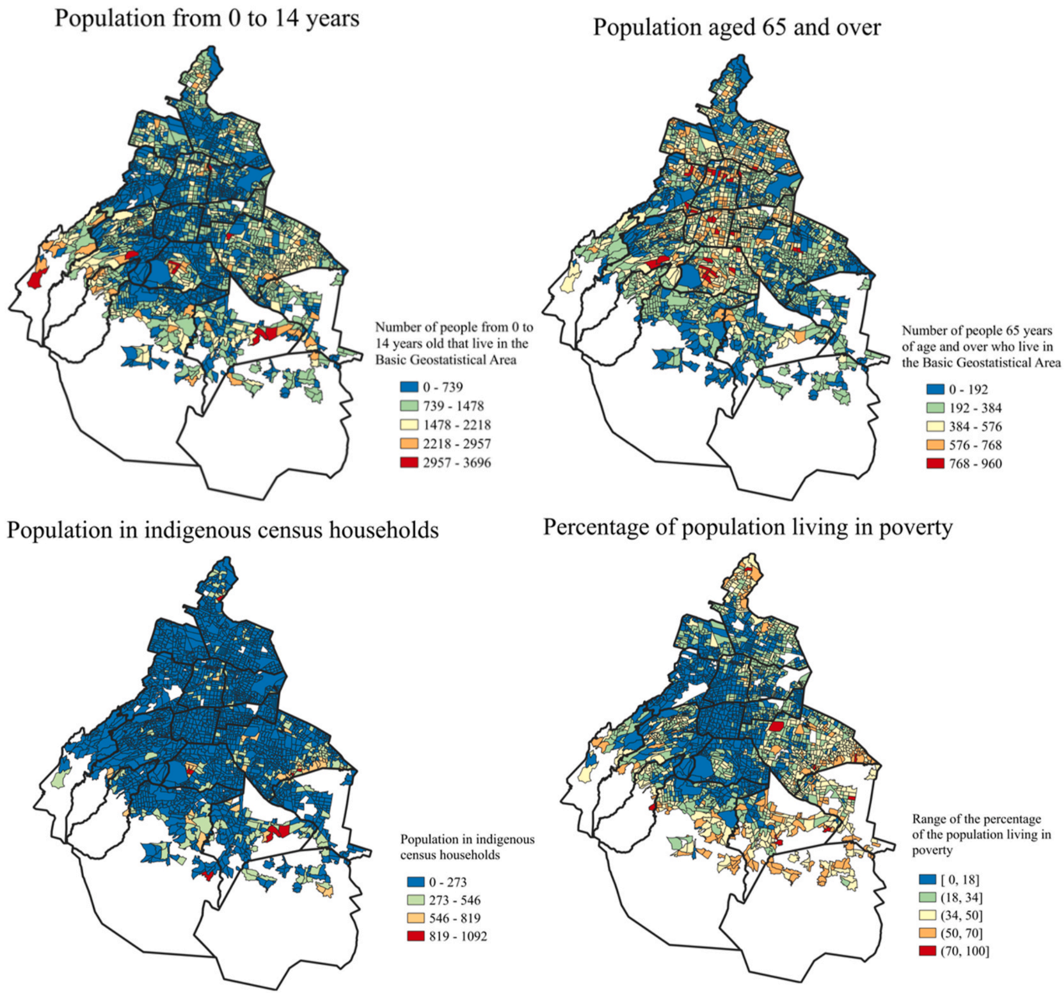

Fig. 5. Sensitivity indicators (population from 0 to 14 years old, over 65 years old, population in indigenous census households, and population living in poverty) at the Basic Geostatistical Areas level, 2010.

evaluate progress or setbacks around actions or objectives, remain a mere instrument that does not fully represent the reality of those who face most of the burden of climate change, that is to say, the people who are most vulnerable. The application and use that is given to the tools will depend on the ontological and epistemological assumptions, the goals or objectives set, as well as on the biophysical, socioeconomic, cultural and governance specificities of each case. As demonstrated in this research, the results of weighing a set of indicators or analyzing isolated indicators, as well as the spatial and temporal scale at which this is done, will be different, an issue that needs to be analyzed and reconciled among social groups with different interests.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2021.102549.

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