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Urban adaptation index: assessing cities readiness to deal with climate change

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Abstract
Worldwide cities are at the forefront of tackling climate change; however, it is not clear to what extent they are prepared for the challenge, particularly in the context of lower income countries, where the need for action is urgent. In this context, many of cities struggle to develop evidence-based approaches to assess their current and future capacity to deal with climate impacts and inform the design of policies to respond in the short/long term. Based both on extensive field research carried out in Brazilian cities and on urban adaptation literature, we develop and test the Urban Adaptation Index (UAI) that cities can use to assess their current adaptive capacity in a realistic/achievable way. The index includes 26 indicators and focuses on a set of public policies to support interventions connected to adaptation: housing, urban mobility, sustainable agriculture, environmental management, and climate impact response. To make the UAI more usable/accessible, we use empirical data that is publicly available, and develop an approach that can be implemented with resources already available in many Brazilian cities. We illustrate the UAI usability by applying the index to the 645 municipalities of the state of São Paulo. Results show that more than half of the municipalities present low UAI ratings; however, municipalities located in metropolitan regions, where the majority of the population live, tend to have higher ratings. Practitioners agreed on the value of the UAI as a tool to monitor the current situation and changes regarding local potential capacity to adapt to climate change.

Keywords Climate change adaptation · Public policies · Sustainability · Index · Adaptive capacity

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1 Introduction

Worldwide cities are at the forefront of tackling climate change; however, it is not clear to what extent they are prepared for the challenge. This is particularly true in the context of lower income countries where many cities struggle to develop evidence-based approaches to assess their current and future capacity to design policies and interventions to better respond and adapt to projected climate impacts. Because climate impacts will likely affect many aspects of urban systems, climate adaptation requires interventions that help cities to solve many of their pressing problems, especially regarding the delivering of social services and the sustaining of environmental resources, while mitigating rising urban greenhouse gas emissions and managing climate related risks (Bulkeley 2010; Carmin et al. 2013; Aylett 2015; Sherman et al. 2016).

Considering vulnerability to climate change as a combination of susceptibility of a system to harm (sensitivity) and capacity of a system to cope and adapt (adaptive capacity) (IPCC 2014), improvements in income levels, education, health status, material assets, and other socioeconomic indicators are important to reduce climate vulnerability overall. Although, given the range of different specific risks that climate change poses to cities, there is also an urgent need to consider specific capacities necessary to overcome and recover (e.g., risk mapping, early warning systems, disaster planning) (Eakin et al. 2014).

Understanding how these capacities combine in cities with different size, socioeconomic indicators, infrastructure, and land use is fundamental for preparing, responding, and adapting to climate change. This understanding is even more critical in the context of lower income countries, where urban settlements are growing rapidly, and are most constrained in terms of adaptive capacity (Paterson et al. 2017). In these cities, effective adaptation planning is still closely dependent on municipal efforts, and governments often lack institutional capacity and operate within strict resource limitations (Ryan 2015; Anguelovski et al. 2016; Chu et al. 2016; Paterson et al. 2017). Moreover, cities in less developed regions often lack data, human capital, and planning resources to inform action (Di Giulio et al. 2018; Araos et al. 2017; Chu et al. 2016).

In this paper, we develop and test the Urban Adaptation Index (UAI) to assess the current potential capacity of cities to deal with climate change impacts. The proposed index is a spin-off of an existing index—the Socio-Climatic Vulnerability Index (SCVI)—which aggregates information on the intensity of climate change with social factors that may influence the vulnerability of the population in a given region (Torres et al. 2012; Darela Filho et al. 2016). The UAI is also a result of the CiAdapta Project that sought to understand how the governments of Brazilian cities address climate adaptation (Di Giulio et al. 2019). Based on the literature, qualitative data related to the local practitioners' information needs, current adaptation aspirations, and existing public data, we both sought to propose and tailor a new index to city level climate adaptation needs while keeping committed to designing a decision-support tool that could be easily updated using data available to the cities.

In line with scientific efforts and the increasing public and political attention to climate adaptation, the UAI includes 26 indicators and focuses on a set of public policies, aggregating information on critical elements to support urban interventions connected to climate adaptation. The index assesses the presence or absence of a legal and regulatory structure to support adaptation, which is very telling of the potential for sustainability and adaptation in a given municipality, albeit it does not assess the results and the effectiveness of public policies. The index combines a set of structural (generic capacity) and climate-specific (specific capacity) elements covered in the scientific literature on urban adaptive capacity, and integrates insights provided by Brazilian municipal practitioners.

With the proposed index, we seek to innovate in relation to other indicators existing in the literature, in two fronts. First, while firmly grounding the conceptualization of our indicators in recent scholarship focusing on urban adaptation and policy-making, we develop indicators that can be crafted using publicly available data such as Census data—in our case, the Brazilian Census. By doing so, the UAI cannot only be easily accessible but also be dynamically updated to reflect rapidly changing cities—a critical constraint in the case of indices that use primary data. Second, by providing a conceptual and methodological approach to evaluate the differences and similarities between the cities' current capacity or lack thereof to deal with climate change impacts and risks, the UAI may actively stimulate debate and emulation between cities, and encourage local governments to design policies that create synergies between adaptation and urban sustainability (e.g., see Kalafatis and Lemos 2017).

To test the UAI and its accessibility, we applied it to the 645 municipalities of the state of São Paulo, Brazil (Fig. 1). These cities make up 21% of the Brazilian population (45 million people) and are responsible for 32.4% of the Brazilian GDP from economic activities.

The article is organized as follows. Section 1 provides an overview of the literature focusing on specificities of adaptation in urban systems in lower income countries and on existing indices for urban adaptation. Section 2 describes in detail the methodology used to build the Urban Adaptation Index. Sections 3 and 4 present the results of the application of the UAI to the municipalities of the state of São Paulo and discuss these results, respectively. We conclude with a few lessons learned and suggestions for future research.

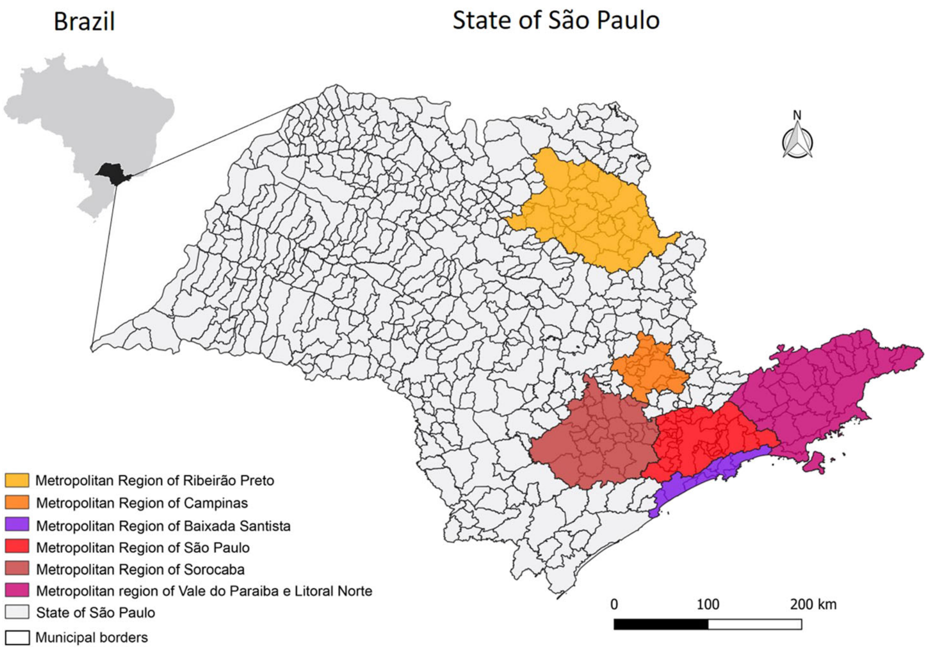

Fig. 1 Map of the location of the state of São Paulo in Brazil, the limits of the 645 municipalities and the six metropolitan regions

2 Adaptation in urban systems

Adaptation is broadly defined as a process of adjustment to the current or expected climate conditions and their effects (IPCC 2014). The literature focused on urban climate governance makes the case that adaptation should be understood as a long-term, iterative, evolving process of change that contributes to climate risk reduction and urban sustainable measures that potentially deliver multiple economic, social, and environmental benefits (Moser and Boykoff 2013; Uittenbroek et al. 2014; Aylett 2015; Broto 2017; Rosenzweig et al. 2018; Runhaar et al. 2018).

Globally, city governments are increasingly introducing adaptation actions to minimize the impacts of climate change. However, the speed of the implementation and the success of the initiatives vary widely (Carmin et al. 2013; Broto 2017; Rosenzweig et al. 2018). The adaptive capacity of a city, understood as its potential to shift to a more desirable position in the face of impacts and risks of climate change, is highly dependent on cultural, social, economic, and political contexts in which the adaptation takes place (Eakin et al. 2014; Wise et al. 2014; Paterson et al. 2017). More precisely, the adaptive capacity of a city can be shaped according to different characteristics: (i) institutions, infrastructure, technologies, and capital markets (Smit and Pilifosova 2003); (ii) the evolution of climate impacts on socioeconomic and financial systems, social, human, and natural resources, and governance (Brooks and Adger 2005); (iii) the availability of resources and the context in which organizations find themselves (Gupta et al. 2010); (iv) the systems of knowledge, environment, economic, livelihood, communication, transportation, organizational, and infrastructure, in addition to the ability to self-organize, flexible responses, asset conversion, and strategy change in periods before and after the event (Moench 2009); (v) and components within institutions that relate informal networks of communication and interpersonal relationships (Adger 2003; Pelling 2010).

Particularly in the context of cities in lower income countries, literature recognizes that urban adaptation should not be considered separately from sustainable development or infrastructure projects that reduce vulnerability and improve the well-being of human subjects and ecosystems (Agrawal and Lemos 2015; Ryan 2015). Building adaptive capacity aligned with sustainability in cities requires measures related to generic capacity (Eakin et al. 2014), including structural elements, policies, and initiatives that address multiple stressors and non-regret measures, in order to (i) address vulnerability and risk in the housing sector (Field et al. 2014; Rosenzweig et al. 2018); (ii) rethink urban mobility to develop more resilient, low-carbon, and inclusive transportation systems (Evers et al. 2018; Rosenzweig et al. 2018); (iii) consider the multiple benefits of sustainable urban and periurban agriculture (Coles and Costa 2018; UN 2018); and (iv) strengthen the environmental management apparatus to deal with water issues (Carvalho et al. 2014) and higher temperatures (Assad and Magalhães 2014). Nevertheless, there is need to create and consolidate the specific capacity regarding elements necessary to overcome climate stressors, including climatic information, preventative and response plans, and infrastructure investments (Carmin et al. 2013; Eakin et al. 2014; Rosenzweig et al. 2018). When combined, both structural (generic capacity) and climate-specific (specific capacity) elements improve the ability of a city to cope with climate change, promote sustainable development, and improve communities' quality of life (Eakin et al. 2014).

However, particularly in the case of cities in lower income countries, where municipal efforts play a key role in adaptation, the combination of pressure from private sectors, insufficient inspection and enforcement, and the mismatch between the scale of urban issues and the extent of local government authority, negatively affect the ability of cities to consolidate adaptation interventions (Di Giulio et al. 2019). Therefore, the use of indices to monitor different instruments that have been used by public management to improve urban sustainability is essential to strengthen the adaptive capacity of municipalities.

Overall, the literature focusing on indices highlight how they are relevant for assessing the performance of jurisdictions and organizations (e.g., cities) when addressing complex phenomena that are not directly measurable and not uniquely defined (Becker et al. 2017), as climate adaptation and adaptive capacity. There is an increasing proliferation of climate change indices, mostly focused on vulnerability indicators and hotspots mapping (e.g., Darela Filho et al. 2016; Lapola et al. 2019; De Sherbinin et al. 2019). The literature also highlights a close relationship between indices of vulnerability, resilience, and urban planning of cities (e.g., Ribeiro et al. 2018; Gargiulo et al. 2020). There are also a large number of articles and indices focused on assessing how municipalities have developed their Climate Change Action Plans (CCAPs) (e.g., Reckien et al. 2018; Grafakos et al. 2020), and others aimed to assess how municipalities have been prepared to cope with climate change (e.g., Heidrich et al. 2013; ARUP 2014).

While these selected examples show that indices can be useful to better understand the relative importance of different drivers of vulnerability and adaptation, they shed light on their limits of usability, due to lack of robust metrics, and lack of data availability and access (Darela Filho et al. 2016; De Sherbinin et al. 2019). Moreover, these indices have in general sought to define measures of adaptation to climate-specific events (e.g., high temperatures) and specific sectors (e.g., water).

In the next section, we provide a detailed description of the methodology behind the construction of the UAI, which combines a set of structural and climate-specific elements and is derived from empirical studies in Brazilian cities.

3 Methodology: creating a new index for urban adaptation

3.1 Index preparation

Two characteristics of the local context had to be taken into account for the development of the index: local climate projections and system of governance. Concerning expected climate impacts for Brazil, these include an increase in the air temperature, possible increase of frequency of droughts and floods, increased frequency of warmer days and nights, a reduction of cold days and nights, and more frequent heat waves (Avila-Diaz et al. 2020; Marengo et al. 2020). Particularly in the southeast region, where the São Paulo State is located, extreme events are also expected to occur, mainly with the precipitation of large volumes of rain in short periods of time, causing flooding, especially in denser and more impermeable areas, and landslides (Assad and Magalhães 2014; Margulis 2017). Regarding the Brazilian system governance, we must acknowledge that the 1988 Federal Constitution divided responsibilities for environmental and social policies among the three levels of government (Federal, State, and Municipal). Therefore, climate change responses require the organization and implementation of policies and measures with the participation of actors from these three levels. Although we recognize that different responsibilities for adapting to climate change are distributed among them, the UAI considers policies that are municipal responsibility.

For the selection of the indicators to be used in the development of the UAI, three main criteria were considered: (i) indicators must be representative of central issues covered in the scientific literature on urban adaptive capacity; (ii) data to build the indicators must be largely available at the municipal level in order to be easily applied, and they must cover instruments or policies that are of municipal responsibility; and (iii) alignment with Brazilian National Adaptation Plan and practitioners insights.

3.1.1 An index based on urban adaptive capacity literature

The UAI considers both generic and specific capacities, including structural and climate-specific elements, and focuses on five sets of public policies to support urban interventions connected to climate adaptation, namely, housing, urban mobility, sustainable agriculture, environmental management, and climate risk management. Table 1 summarizes the five dimensions of the Index and how they relate to climate adaptation according to the literature presented in section 1 of this paper. A description of the indicators used for each dimension is also presented.

3.1.2 An index that is relevant and applicable at municipal level

The UAI is an index that aggregates information on critical elements that may influence a city's capacity to initiate or implement urban-climate adaptation, minimizing the expected impacts on municipal territories. Given the diversity of cities (in terms of sizes, incomes, and levels of access to infrastructures), the criteria for choosing the dimensions and indicators used in the UAI should be comprehensive enough for any municipality (and its urbanization process) and be represented by currently available data. Therefore, we acknowledge that the UAI includes only some critical components of adaptive capacity, which were intentionally selected following these criteria. Data for the 26 indicators is derived from the most recent and widely available census municipal statistical data, the Profile of Brazilian Municipalities of 2017 (IBGE 2018). Based on official data source, which are often collected, this set of indicators can be dynamically updated, allowing a continuous and comparative assessment of the potential capacity of cities to deal with climate change impact.

Moreover, we verified, thanks to the feedbacks of cities practitioners, that the indicators are linked to instruments and policies that are responsibility of the municipalities.

3.1.3 An index that is aligned with the Brazilian National Adaptation Plan and practitioners' insights

In addition to being based on literature, the validity of the indicators was verified and guaranteed in two ways. First, we verified the coherence between the dimensions and indicators of the UAI with strategies and actions included in the Brazilian National Adaptation Plan to Climate Change (Brasil 2016). The plan covers a range of guidelines divided in different themes and sectors, including agriculture, biodiversity and ecosystems, cities, natural disasters, industry and mining, infrastructure (encompassing energy, transport and urban mobility), vulnerable people and populations, water resources, health, food and nutrition security, and coastal areas. We identified great coherence between the UAI and the National Adaptation Plan, proving the relevance of the indicators considered (see supplementary material).

Table 1 Proposed dimensions and indicators to the UAI

Dimensions	Connections to climate adaptation	Indicators
Housing	a) Addressing vulnerability and exposure in the housing sector is critical to guarantee access to safe and secure land, and reduce risks in cities, particularly in informal settlements, where increases in the frequency and intensity of extreme weather events present the greatest risks (Rosenzweig et al. 2018) b) Identifying risk areas where settlements are located on slopes, riverbanks, and reservoirs, with a scarcity of drinking water and sanitation, poor distribution of public services, and where building conditions are precarious, is crucial to making choices that improve quality of life, and reduce risks and losses (Field et al. 2014)	1.Municipal housing plan: means that the city is aware of the need for a reference instrument that articulates housing precariousness with economic dynamics and population growth (a, b) 2. Municipal council: indicates that decisions on this sector might be shared, engaging the residents (a, b) 3. Municipal funding: indicates that there are financial resources for the application of the proposed housing measures (a)
Urban mobility	c) Climate-related shocks to urban transportation have economy-wide impacts, beyond disruptions to the movement of people and goods; thus integrating climate risk reduction into transport planning and management is necessary in spatial planning and land use regulations (Rosenzweig et al. 2018) d) Low-carbon transport is more socially inclusive, and a diversified and secure transportation system might be helpful in case of critical extreme events where evacuations may be necessary (Eichhorst 2009) e) In order to minimize extreme climate events impacts, municipalities should increase road shading, use more resilient design materials and standards to build infrastructures (Eichhorst 2009) f) There is a need for transit-oriented development (Evers et al. 2018)	4. Municipal mobility plan: means that the city has an instrument that can define the allocation of resources and guide the development of the municipal transportation system, making it more sustainable; the existence of this municipal plan is a condition for getting federal resources, according to the National Policy on Urban Mobility (Brasil 2012) (c, d, f) 5. Cycle lane: indicates that individual non-motorized transport infrastructure is supported by the city (d, e) 6. Bicycle racks: indicates that individual non-motorized transport infrastructure, intermodal integration and system flexibility are supported by the city (d, e) 7. Intermunicipal public transport: means that collective public transport infrastructure is supported by the city (d, e, f) 8. Intramunicipal public transport: means that collective public transport infrastructure is supported by the city (d, e, f)
Sustainable agriculture	g) Urban and periurban agriculture increase food security in urban areas, serve as an effective measure to contain the advance of urban sprawl into protected areas, promote job opportunities and increase the green and permeable areas in the municipality (UN 2018) h) The effects of climate change should impact food production in all regions; there is a need to adapt local agriculture to changes in temperature and water availability (Assad and Magalhães 2014) i) Urban agriculture brings food production closer to consumers, reducing losses in transit; promoting healthy lifestyles, social integration, participatory spatial practices (Coles and Costa 2018)	9. Organic agriculture: means that the city has programs or develops actions that support organic agriculture (g, h, i) 10. Family farming: means that the city has programs or develops actions that support family farming (g, i) 11. Community gardens: indicates that the city has programs or develops actions that support community gardens (g, i) 12. Climate program for agriculture: indicates that the city has a program focused on climate risks and the impact on agriculture (h) 13. Program for associativism: indicates that the city supports programs to support associations of farmers and cooperatives that create conditions for rural producers to

Table 1 (continued)

Dimensions	Connections to climate adaptation	Indicators
		structure and maintain (economically) sustainable production systems (g, i)
Environmental management	j) Climatic impacts put pressure on water availability for human and animal consumption, increasing the importance of basic sanitation policies, protection of water resources, and revitalization of water producing areas (Carvalho et al. 2014) k) The increase in average temperatures increases the risks related to respiratory diseases, especially in children and elderly people and, when associated with peak precipitation events, influences the dissemination and dynamics of vector-borne diseases, situations potentiated with the occurrence of floods (Assad and Magalhães 2014; Field et al. 2014) l) Water security challenges extend to periurban areas as well, where pressure on resources is acute, and where there are often overlapping governance and administrative regimes; adaptation measures can minimize negative impacts in the long term (Rosenzweig et al. 2018) m) Cities could benefit from low-carbon energy production and improved health with wastewater treatment (Rosenzweig et al. 2018) n) The municipal authority's ability to improve solid waste management provides opportunities to mitigate climate change and generate co-benefits, such as improved public health and local environmental conservation (Rosenzweig et al. 2018) o) Investing in green infrastructure can reduce urban heat and flooding through its shading, evaporative, interception, and infiltration capacities (Derkzen et al. 2017) p) Ecosystem-based adaptation (EbA) plays an important role in urban contexts because it includes management, conservation, and restoration of ecosystems that deliver services that could help reduce climate change exposures (Brink et al. 2016; Geneletti and Zardo 2016) and allow cities to introduce more critical discussions of socioeconomic vulnerability (Chu et al. 2017) q) EbA offers the advantage of promoting "no regrets" interventions and potentially delivers multiple economic, social, and environmental co-benefits that go beyond climate adaptation (Cortekar et al. 2016; Geneletti and Zardo 2016)	14. Municipal environmental funding: indicates that the city has a specific budget for the promotion of environmental protection policies (j, k, l, m, n, o, p, q) 15. Sanitation: indicates that the city has a specific law or related instruments for sanitation (j, k, l, m) 16. Environmental protection: means that the city has a specific law or related instruments for protecting or controlling the environment (j, l, n, o, p, q) 17. Air pollution: indicates that the city has a specific law or related instruments for controlling air pollution (k, m, o, p) 18. Biodiversity protection: indicates that the city has a specific law or related instruments for protecting biodiversity (k, o, p, q) 19.Climate adaptation and mitigation: indicates that the city has a specific law or related instruments for promoting climate adaptation and mitigation (j, k, l, n, o, p, q) 20. Integrated solid waste management plan: indicates that the city has a municipal plan according to the National Policy on Solid Waste (n) 21.Environmental services payment: indicates that the city pays for environmental services (j, k, l, o, p, q)
Climate impact response	r) Climate impact stressors are expected to compound serious problems associated	22. Law of land use and occupation related to flood prevention: indicates that the city has

Table 1 (continued)

Dimensions	Connections to climate adaptation	Indicators
	with historically haphazard processes of urbanization (Rosenzweig et al. 2018) s) Developing integrated actions coordinating between multiple planning and operational procedures might contribute to implementing interventions that can help cities solve some of their pressing municipal service delivery and urban environmental problems (Carmin et al. 2013). t) Specific climate adaptation actions may involve preventive and response plans, alert and monitoring systems, risk mapping, and/or simulations that help the city overcome climate stressors (Eakin et al. 2014)	a specific law for land use and occupation that considers flood prevention (r, s, t) 23. Law of land use and occupation related to landslide prevention: indicates that the city has a specific law for land use and occupation that considers landslide prevention (r, s, t) 24.Municipal plan risk reduction: indicates that the city has an instrument to identify its geological and physical risks, and define interventions and investments to minimize the impacts (r, s, t) 25. Geotechnical chart of suitability for urbanization: indicates that the city has an instrument to support urban planning, providing guidelines for land use and occupation based on the analysis of the physical characteristics of the land, and on the forms of land occupation (r, s, t) 26. Municipal civil defense: means that the city has a specific municipal government sector to deal with a range of impact stressors, including climate risks (r, s, t)

Second, the indicators take into account insights provided by Brazilian municipal practitioners who had attended interactive workshops, conducted between 2016 and 2019, in six large Brazilian municipalities: São Paulo, Manaus, Porto Alegre, Curitiba, Vitória, and Natal (Di Giulio et al. 2019) (see supplementary material). The qualitative analysis of their inputs, in consonance with the updated literature, was crucial to reflect on and identify relevant policies for adaptation in Brazilian municipalities that enable mainstream adaptation measures across different policy sectors and available budgets, both addressing multiple stressors and non-regret policies, and fostering the needed integration of municipal departments to create synergies between adaptation and urban sustainability. Furthermore, the UAI and the results from its application to the municipalities of the state of São Paulo were discussed in a workshop with 17 participants, including 7 academic researchers with experience in the field of climate change adaptation, and 10 representatives of the public sector from the State level, who are responsible for the elaboration of the Ecological Economic Zoning (EEZ) of the state of São Paulo, and have a deep understanding of the particularities and vulnerabilities of each region of the state of São Paulo and its municipalities. Considering the impossibility of collecting the opinions from representatives of all the 645 municipalities, it was decided to carry out the index validation with this selective group of State civil servants. The interactive workshop was organized by the research team, and the participants were identified and invited through a purposive and selective sampling approach, based on the meeting organizers' knowledge and experience. In the first part of the workshop, the research team presented the index and its results. Then, the civil servants were invited to express their impressions regarding the proposed index, shedding light on its accessibility and usability.

3.2 Index calculation

The UAI is a measurement index, meaning that information on the existence (or absence) of public policies does not necessarily indicate consolidated interventions; instead, it suggests that there is a legal, institutional, and/or regulatory structure to support (current or future) urban interventions connected to climate adaptation. Based on dichotomous information from the Profile of Brazilian Municipalities of 2017 (IBGE 2018), we used a rating scale (0 (non-existence) to 1 (existence)) in order to score the UAI. Since the five dimensions vary in the number of indicators, the results were normalized to assign the same weight/ importance to each dimension. The normalization was done by the simple arithmetic mean of the indicators scores for each of the five dimensions, providing a result that also varies from 0 to 1, regardless the number of indicators that constitute each dimension. Once each dimension has an equal weight within the UAI (20%), the simple arithmetic mean of the sectorial results provides the UAI score for that municipality, defined as:

$$\mathrm{UAI} = \frac{1}{N} \sum_{i=1}^{N} PI_i$$

where PI_i is the partial index PI for the dimension I, and N is the total number of dimension (5 in this study).

After calculating the UAI score for each municipality (including partial scores for each of the five dimensions), the results were entered into a Geographic Information System software in order to produce the maps. Results are also presented in a format that can show the correlation of UAI score with the overall population and seven cities categories based on the number of inhabitants (< 5000 inhabitants; 5001–10,000; 10,001– 20,000; 20,001–50,000; 50,001–100,000; 100,001–500,000; > 500,000).

While the proposed 26 indicators have impacts on urban areas and population, they are applied for the entire municipality (which, in Brazil, may include urban, rural, and natural areas, depending on the local regulation). In consonance with the literature and based on insights provided by the Brazilian practitioners, we recognize that urban areas have strong linkages with rural (Davoudi and Stead 2002) and natural surroundings (Haase 2017), and this should not be neglected in urban adaptation processes.

4 Results: application of the UAI to the state of São Paulo

In this section, we present the results from the application of the UAI to the 645 municipalities of the state of São Paulo. The maps (Fig. 2), each representing one of the five dimensions of the index, and one final map representing the overall UAI results, allow for communicating the results in a visually intuitive way and providing an accessible snapshot of the current level of potential capacity for adaptation in the state of São Paulo.

In the Housing dimension (Fig. 2a), we identified that almost half of the state's municipalities (48.5%) do not have municipal housing plans, councils, or funds, while only 19.7% have all of the above. The municipalities with the lowest rates are in the western region of the state, while those with the highest rates are mainly in the metropolitan areas in the eastern part

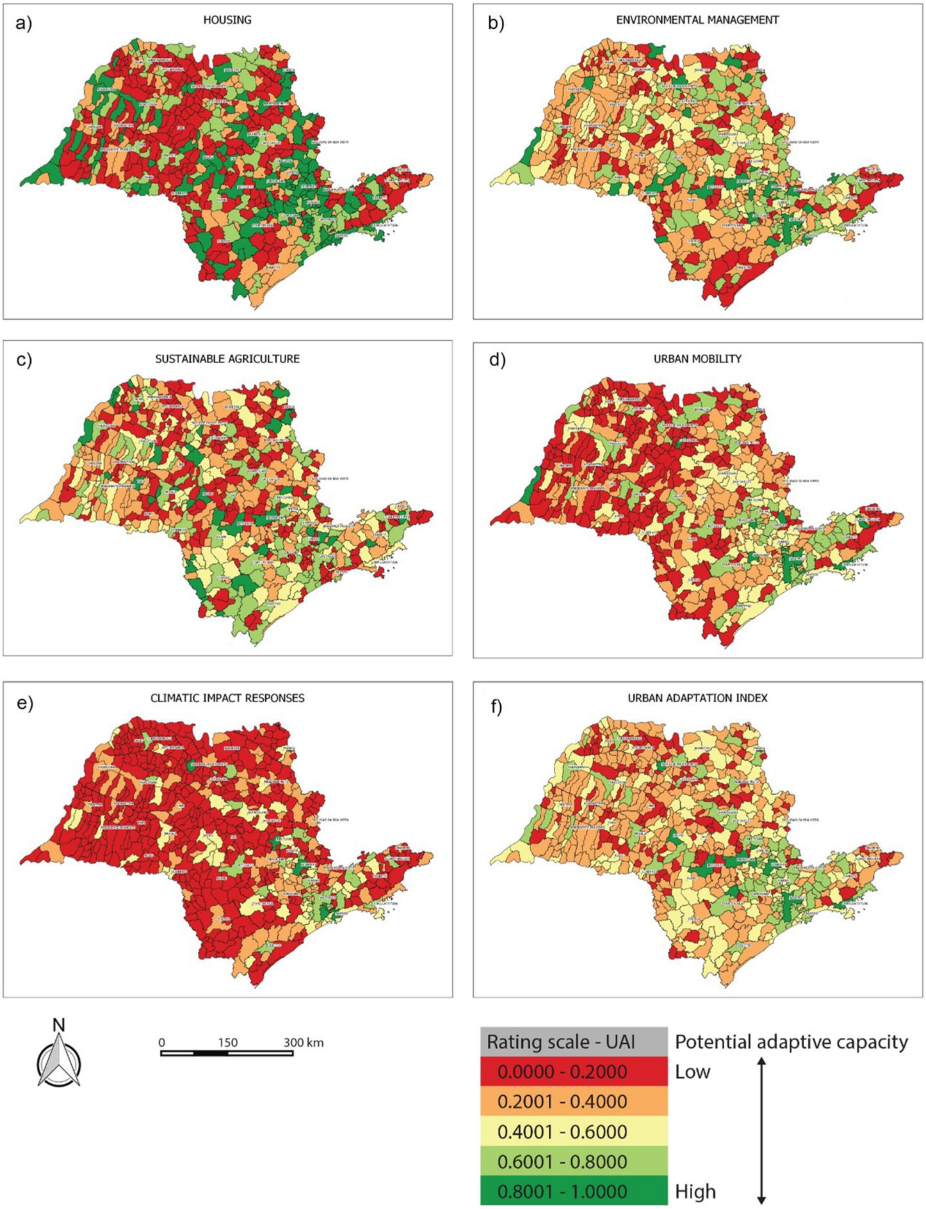

Fig. 2 Maps of the five dimensions of the UAI and the overall UAI results in the state of São Paulo, Brazil: **a** housing; **b** environmental management; **c** sustainable agriculture; **d** urban mobility; **e** climate impact responses; **f** overall Urban Adaptation Index

of the state. In addition, we observed that the municipalities with the highest scores in the housing dimension are in the most densely populated areas of the state, mainly in the large cities and metropolitan regions.

The results for the environmental management dimension (Fig. 2b) are unequally distributed across the state and do not reveal a clear relationship between larger, more populous municipalities and the highest ratings. Within this dimension, the indicator with the highest score is related to the existence of an integrated solid waste management plan, which was present in 76% of the municipalities, while the lowest indicator was related to the specific capacity of the municipality to respond to impacts of climate change, present in only 5.6% of the municipalities. A particularity of this dimension is the low rate in the southern region of the state and, to a lesser extent, in the southeast. The sustainable agriculture dimension has high scores in the same geographical area, showing a disparity of efforts and focus in terms of government actions in these two dimensions. This is also particularly important because the municipalities in the south of the state still make up about 30% of its native vegetation, revealing the need for greater action in local environmental management.

The dimension of sustainable agriculture (Fig. 2c) has the most uniform spatial distribution across the state compared to the other dimensions. With 188.600 agricultural sites (IBGE 2017), there is a great diversity of these activities throughout the state, particularly in the southern municipalities. This resulted in high scores in this area, as there are more actions being undertaken to strengthen the local sustainable agricultural practices. The programs to stimulate family farming and associativism were the most prevalent indicator in the state, found in, respectively, 71.3% and 63.6% of the municipalities. Actions aimed at stimulating organic agriculture and the production of community gardens were identified in 30% of the state's municipalities.

Regarding urban mobility (Fig. 2d), most of the municipalities with the highest ratings are in the metropolitan regions of the state. The absence of municipal transportation plans in the state of São Paulo follows a national trend, in which only 7% of Brazilian municipalities have such a plan, mainly in large cities with over 500.000 inhabitants (IBGE 2018).

The climate impact responses dimension (Fig. 2e) was the one with the lowest results in general. About 70% of the municipalities of the state do not have any or have only one of the instruments considered, while only seven municipalities have all the instruments and only one is from outside a metropolitan region. A notable finding highlighted by the index is that, although most of the municipalities of the state have a civil defense coordination (77%), this is not reflected in the existence of the other instruments, such as the municipal risk reduction plan (17,4%) and the geotechnical charts (8.4%).

The final map (Fig. 2f) represents the overall results of the UAI in the state of São Paulo. The map reveals a concentration of municipalities with the highest ratings of the UAI in the southeastern area of the state, while the ones with the lowest are located mostly in the west and northwest of the state.

As can be observed in Fig. 3, the application of the UAI to the municipalities of the state of São Paulo shows that the majority of the municipalities (66%) are located in the two lower ranges of the index. One hundred twenty-seven municipalities range between 0 and 0.2000 and 298 municipalities between 0.2001 and 0.4000. In the intermediate range, which includes municipalities with UAI ranging from 0.4001 to 0.6000, there are 137 municipalities, corresponding to 21.2% of São Paulo's municipalities. The two upper levels of the UAI are composed of 12.87% of the municipalities, 73 of which are in the range between 0.6001 and 0.800 and only 10 municipalities received ratings that varied between 0.8001 and 1, the equivalent of 1.55% of the municipalities in São Paulo.

Although the results show cause for concern, only 12.2% of the state's population are concentrated in the two lower ranges of the UAI. Figure 3 also clearly shows that the most populated municipalities (with 50.000 inhabitants or more) tend to score better than municipalities with fewer inhabitants. Thus, it is important to observe that even if the majority of the

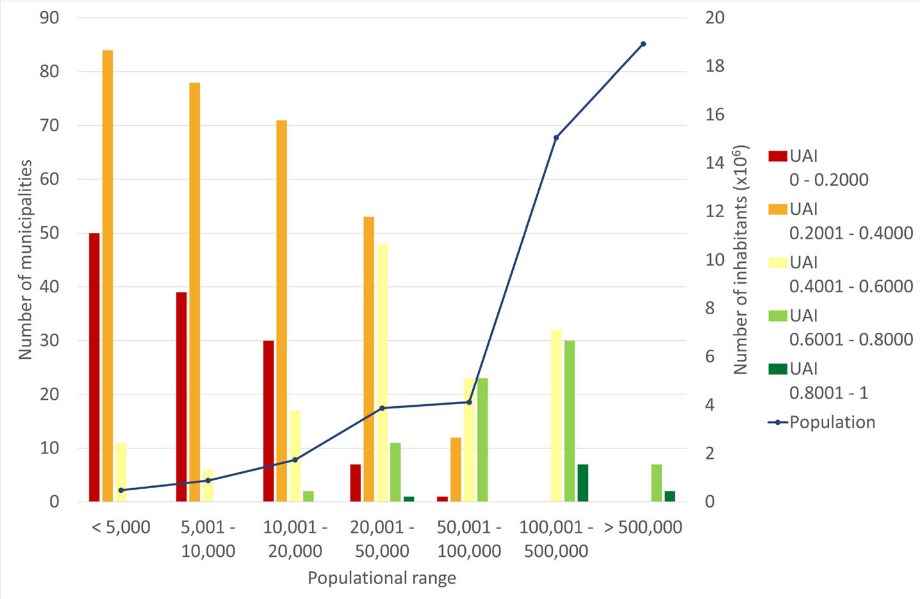

Fig. 3 Relation between number of municipalities, population, and UAI scores in the state of São Paulo, Brazil

municipalities of the state of São Paulo are located in the lower ranges of the UAI with lower adaptive capacity, the majority of the state's population lives in municipalities with better indicators at the higher ranges of the UAI.

5 Discussion

Although the UAI was applied at the municipal level, it is possible to identify regional trends from the analysis of the map depicting the overall results. In fact, the municipalities that are located within the metropolitan regions of the state of São Paulo (see Fig. 1 in the introduction), where most of the population of the state is located, tend to show the highest scores. It is important to note that these metropolitan regions are governed by the Metropolis Statute that can directly influence the development of several instruments considered in the five dimensions of the UAI (e.g., public funds, compensation for environmental services provided by the municipality and the elaboration of integrated urban development plans). Integrated urban development plans, for example, must provide the delimitation of areas with urbanization restrictions, either due to the protection of environmental and cultural heritage or to the presence of areas subject to special control because of the risk of natural disasters (Brasil 2015). Therefore, this results in higher scores for most of the municipalities of the metropolitan regions.

The higher scores in metropolitan regions can also be observed within some of the dimensions of the index. In the housing dimension, for example, it was possible to determine that the highest ratings were obtained in the most populated municipalities, mainly located in the metropolitan areas. This highlights a greater concern for this issue in areas where there is a larger population and, consequently, a greater need for housing organization. This results in the application of a set of tools for managing the municipal housing issue, either by political will or legal obligation. For municipalities with a smaller population, where housing is not an urgent issue, the use of this index may contribute to improving urban planning and the improvement of the population's quality of life.

The urban mobility dimension also showed this trend, due to the fact that the smaller cities in the state usually do not consider mobility as an issue or necessity. Smaller cities in the western part of the state, for example, do not need to deploy their own bus fleets, but they can encourage actions that reduce people's dependence on individual motor vehicles and expand the mobility options available to the population, including bicycle lanes, improvements to sidewalk conditions to encourage walkability, or the implementation of alternative public transport.

The environmental management dimension was unequal throughout the state and did not have a direct relation with the metropolitan regions and/or most populated areas. The low percentage of municipalities in the state that have laws aimed at protecting biodiversity (14.1%) indicates that this is a critical aspect that must be considered by the local governments. The sustainable agriculture dimension also did not have a direct relation to the most populated areas, as the agriculture sites are located all over the state's territory. The indicator for the development of a program or action to prevent climate problems for the agricultural sector in this dimension was identified in only 17.4% of the municipalities, highlighting the need for public awareness of and action on this issue (Marengo et al. 2016).

In the climate impact responses' dimension, the higher results in the metropolitan regions can be explained by (a) their higher population concentration, which requires greater knowledge of the location to protect the population against extreme weather and climate events; (b) the presence of regulatory agencies, pressuring the public sector to act in accordance with the regulations; and (c) the master plans and integrated urban development plans in these areas, contributing to the occupation and land use laws and delimitation of areas of urban expansion, elements that were evaluated in this dimension.

5.1 Potential for adoption in climate governance

Generating climate information that is salient, useful and relevant may not necessarily result in its usability or in better decision-making (Lemos et al. 2012; Serrao-Neumann et al. 2020). While we argue that one relevant innovation of the UAI is its capacity to be dynamically updated by using publicly available data, we also appreciate that the index's potential for usage in policy is essential to strengthen the adaptive capacity of municipalities—or at least to foster a more qualified debate on urban climate adaptation. Bringing such index and maps to a local geographic scale stimulate decision-makers to feel more entitled to discuss these data, and encourage them to take action. In this sense, the interactive workshop organized to present and discuss the index and its results with the civil servants sheds light on positive perspectives of the UAI regarding its accessibility and usability. The participants emphasized the relevance of the index, highlighting its potential for mainstreaming adaptation measures across common municipal policy sectors, addressing multiple stressors that commonly affect the municipalities. Mostly, given the cross-acting nature of effective responses to climate change, they recognized the potential of the UAI for involving technical competence of staff in multiple planning and operational procedures, fostering the required integration of municipal departments to create synergies between adaptation and urban sustainability. Besides their expectations of how the index may fit the local decision-making process regarding climate adaptation, the participants recognized the consistency and usability of the obtained results to the current EEZ process, which main goal is supporting the formulation of public policies, having the resilience to the impacts of climate change as one of its main guidelines.

5.2 Caveats

Although the UAI gives important insights as to what extent cities are prepared to deal with climate change impacts, we acknowledge some of its limitations. The UAI assesses the potential capacity of a city to adapt to climate change; however, we recognize that other general governance indicators, such as transparency, accountability, and corruption levels, which are critical to municipal adaptive capacity, are not considered as they are not available at municipal level in the state of São Paulo. Furthermore, the index does not consider sensitivity indicators and consequently it does not give information about the municipality’s level of vulnerability. The UAI provides the necessary information for addressing adaptation issues across different policy sectors (Uittenbroek et al. 2014); however, it should not be considered a normative tool, but rather an informative one. We acknowledge that the index has been applied to all the municipalities in the same way, regardless of the size, population, mandatory of certain tools for larger municipalities (e.g., municipal mobility plan is mandatory for municipalities with more than 20,000 inhabitants and exceptional situations), or land use characteristics (e.g., tools that support sustainable agriculture are more likely to be present in municipalities with extensive agricultural areas). Nonetheless, the index and the disaggregated indicators shed light on the gaps, in terms of policies and tools, that hinder a city’s potential capacity to deal with climate change. Local governments should be able to prioritize improvements in the most critical sectors, which may vary for each municipality according to local priorities. Therefore, the selection of policies or instruments to be implemented should be made according to the regulatory, social, environmental, and economic characteristics of each location. We recognize that most of municipalities with higher degrees of urbanization, usually with more population, have greater scores. For future studies, it would be useful to add and/or exclude indicators depending on specific characteristics and scale and the population of the cities.

6 Conclusions

The scientific community and international organizations agree on the importance of the role of cities and local authorities in addressing climate change adaptation. However, there is little knowledge of the progress being made in cities and the extent to which they are prepared to cope with climate change. It is also worth highlighting that, particularly in the context of Brazil and in lower income countries, it is important to focus on strategies specifically designed not only to deal with climate change impacts, but also to mainstream adaptation measures across different policy sectors, thereby ensuring coherence between adaptation and urban sustainability. In order to understand and monitor the current status of, and assess required changes to, the local potential capacity to adapt to climate change, we developed the UAI. The UAI is derived from empirical studies of Brazilian cities, and composed of 26 indicators that cover the most relevant dimensions of urban adaptation according to the literature: housing, urban mobility, sustainable agriculture, environmental management, and climate impact response. The UAI was then applied to the 645 municipalities of the state of São Paulo, Brazil.

Results show that more than half of the municipalities in the state of São Paulo present low UAI ratings. However, the municipalities located in metropolitan regions, where the majority of the population lives, tend to have higher ratings.

The UAI proved to be a useful tool to understand the current situation of the municipalities of the state of São Paulo in the adaptation process. The index provides information regarding the existence (or nonexistence) of legal, institutional, and/or regulatory structures to support current or future urban interventions connected to climate adaptation. However, this is only a basis for each municipality to understand where they are in the adaptation process and where they should act to increase their potential capacity to adapt to climate change. The actual need for improvements in each dimension of the UAI should be evaluated according to the specific characteristics of the municipality (e.g., size, land use characteristics, results of vulnerability and risk assessments, and mandatory of certain tools for larger municipalities).

The composition of the UAI and the results of its application were discussed and positively assessed by researchers and representatives of public administration bodies at the State level. Practitioners particularly agreed on the value of the UAI as a tool to monitor the current situation and changes in the local potential capacity to adapt to climate change.

We recognize that the index was applied to a very specific context, in the richest and most developed state of the country, but it is also worth highlighting that availability of the selected data used in the index for the entire country and ease of implementation by institutional actors make it possible to apply the UAI to all Brazilian municipalities. This would provide an overview of the country and help to identify potential shortcomings that did not emerge from the test in the state of São Paulo. Through the scaling up of this research, all the municipalities across the country can make use of the basic information to strengthen their potential adaptive capacity, and the index itself can be refined. In addition, the UAI can be used in other countries, especially in the context of middle-income countries in the Global South, as long as a certain availability of information is granted and specific administrative and regulatory indicators are considered, especially those related to management, regulation and planning tools.

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Declarations

Competing interests The authors declare no competing interests.

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