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Published in:
Ecological Indicators

Link to article, DOI:
10.1016/j.ecolind.2023.110078

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Ecological Indicators 148 (2023) 110078

Contents lists available at ScienceDirect

Ecological Indicators

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

Review

Identifying barriers and potentials of integrated assessments of sustainable urban development and adaptation to rising sea levels

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ARTICLE INFO

Keywords:
Sustainable urban development
Coastal adaptation
Indicators
Sustainable adaptation
Urban systems
Flood Vulnerability

ABSTRACT

Current adaptation responses to sea-level rise tend to focus on protecting existing infrastructure resulting in unsustainable adaptation pathways. At the same time, urban development compromises a city's adaptive capacity if the climate risk component is ignored. While fighting for the same space, these two domains are currently widely analyzed separately. This paper develops a framework for integrating sustainability assessments of sustainable urban development (SUD) and coastal adaptation to climate change (CACC). Through a systematic literature review, we collected more than 2,700 indicators for SUD and 1,800 indicators for CACC. The indicators occurring most frequently are extracted and structured into frameworks. The study highlights the differences and similarities between the two frameworks. We further identify complementary and conflicting objectives that can advance or inhibit the effective integration of SUD and CACC. CACC tends to focus on assessing specific adaptation measures and their immediate impact on the city's vulnerability, ignoring wider impacts on socioeconomic systems. SUD considers the city and its functions as a whole but ignores vulnerability assessments across urban subsystems. We develop a combined framework for sustainability assessment that may serve as a basis for both qualitative and quantitative integrated studies under the paradigm of sustainable adaptation.

1. Introduction

Human activities have led to an irreversible "[im]balance between economic activity, population growth, infrastructure and services, pollution, waste, noise, etc." (Hiremath et al., 2013), having caused and accelerated climate extremes (IPCC, 2022). In light of inevitable climate change impacts and associated socioeconomic costs, adaptation efforts have become critical. Rising sea levels and corresponding changes in flood risks due to storm surges are amongst the most detrimental climate change impacts. Yet, urban areas expand faster in low-elevation coastal zones than anywhere else (Seto et al., 2011). Uncontrolled urban development in flood-prone areas may lead to lasting damage to societies or trigger the development of structural protection measures that are unsustainable from an environmental as well as an urban welfare perspective (Di Baldassarre et al., 2018; Thomsen et al., 2012).

Despite the consensus that adaptation must be an integral part of sustainable urban development (IPCC, 2022), several examples from practice demonstrate that urban planning practices and flood-risk adaptation still frequently fail to develop integrated visions that can lead to unsustainable adaptation pathways (Aerts et al., 2018). Two international examples are excellent showcases:

1) From 1953 to well into the new millennia, The Netherlands followed a paradigm of continuous heightening and strengthening of dikes, which was challenged by increasing volumes of water flow, dike overflows, and breaches leading to severe flood damages (De Bruijn et al., 2015). The Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) had to acknowledge that the dike strategy cannot continue indefinitely and that more holistic flood risk management approaches are needed (Busscher et al., 2019).
2) Copenhagen's Climate Adaptation Plan envisions a "long-term, broad and focused effort to bring about a greener Copenhagen" as "a preventive investment in a climate-proof Copenhagen" (City of Copenhagen, 2011). The reality, however, does not reflect this endeavor: An analysis by SMVdanmark (2020) showed that the total size of green areas in Copenhagen decreased between 2011 and 2018, despite population growth.

The literature highlights two main reasons for the lack of integration

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https://doi.org/10.1016/j.ecolind.2023.110078
Received 21 November 2022; Received in revised form 15 February 2023; Accepted 26 February 2023
Available online 3 March 2023
1470-160X/

of the domains of sustainable urban development (SUD) and coastal adaptation to climate change (CACC): (1) institutional and governance arrangements (Busscher et al., 2019; Hurlimann et al., 2014), and (2) differences in conceptualizations and framings of planning domains (Engle, 2011; Spiller, 2016). Conceptualizations guide the kinds of activities that actors may take and the degree to which they can either promote change or maintain the status quo (Meerow and Newell, 2016; Olewiler, 2006; Shen et al., 2011). Thus, differences in conceptualizations of planning domains reflect different assessments of conditions and trends that may lead to siloed activities adversely affecting each other.

An efficient way to elicit these conceptualizations is by considering the quantitative indicators and indices that are being applied within each assessment framework (e.g., Gallopín, 1997; Huang et al., 2015). Hence a critical review and comparative analyses of indicators and their implicit conceptualization will enable a better understanding of (1) the lack of integration between the two domains and (2) the reasons why unsustainable adaptation pathways occur. We will therefore review indicator frameworks for SUD and CACC as a means of operational representations of each domain and analyze the interplay between them. More specifically, we aim to understand:

- how concepts of SUD and CACC are understood in scientific and applied literature,
- how conceptual differences inhibit the integration of the planning domains;
- on what aspects the two planning domains benefit or compromise each other and how this is reflected in practice.

To achieve these objectives, we perform a systematic review of objectives and indicators for both planning domains of SUD and CACC with the aim of making them comparable. Based on the outcome of the review, we highlight differences in conceptualizations to better understand the barriers and potentials of integrating SUD and CACC. While there is a vast number of indicator reviews focusing on urban sustainability (Hiremath et al., 2013; Huang et al., 2015; Merino-Saum et al., 2020), only a few reviews of indicators for climate change adaptation exist to date (Arnott et al., 2016; Salehi et al., 2019) and none of them appear to focus on the city scale and on adaptation to rising sea levels. Furthermore, no comparative review studying both domains of SUD and CACC has been conducted as of yet. The main contribution of our work is to develop a common framing for sustainability assessments that integrates both domains with a common language and structure that can form the basis for subsequent quantitative integrated assessments.

2. Methods and data

Fig. 1, part A illustrates the five methodological steps conducted in this study: (1) collecting indicator sets and frameworks, (2) selecting indicator sets, (3) structuring indicator sets, (4) extracting indicators, (5) consolidating results including a comparative analysis of frameworks. Fig. 1, part B and C show the detailed sub-steps of the structuring and

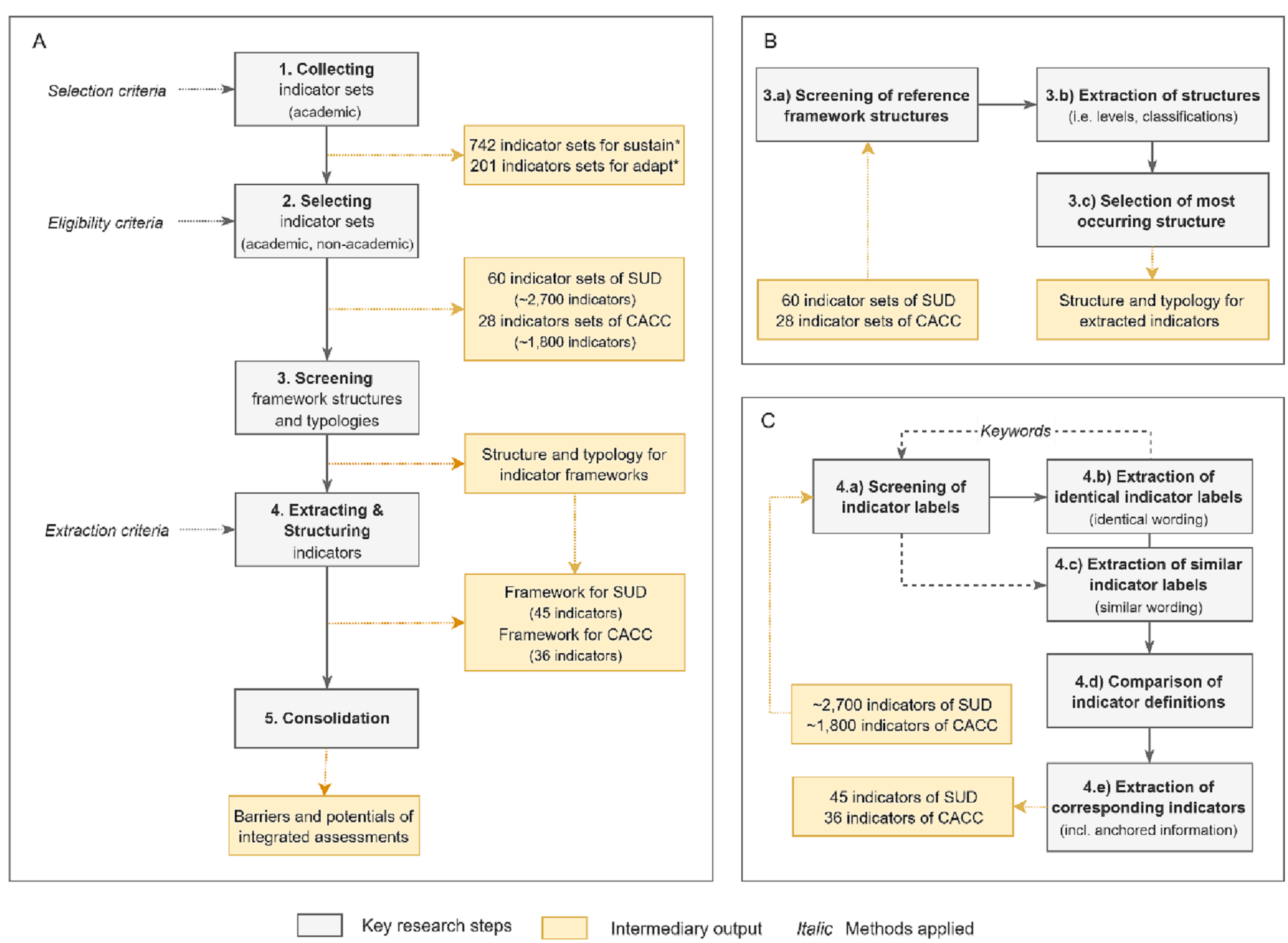

Fig. 1. A: Visual overview of the steps involved in the review: Key methodological steps conducted in the present study; B: Sub-steps in step 3 (Screening of framework structures); C: Sub-steps in step 4 (Extracting of indicators) (see online version for color representation).

extraction process.

In this study, we refer to an indicator set as "group[s] of non-aggregated indicators often organized following a certain [conceptual] indicator framework" (Huang et al., 2015). Here, a framework is understood as a structure, system, or plan consisting of descriptive categories and their relations in which indicators are anchored. Furthermore, an indicator framework reflects the way a subject under study is understood and may provide guidance in specific areas (Merino-Saum et al., 2020).

2.1. Collection of indicator sets and frameworks

To ensure a comprehensive and representative collection of indicator sets and frameworks from theory and practice, academic as well as non-academic literature from public, private or non-profit entities were considered. Academic search engines and the snowball-sampling method were used to identify academic and non-academic literature. For both types of literature, the following selection criteria were applied: only documents published from 2010 onwards and written in English.

2.1.1. Collection of SUD indicator sets

For the collection of SUD indicator sets and frameworks, a literature review in the Web of Science search engine identified academic documents. We included the search terms "index" and indices" as they sometimes denote quantifiable indicators and the terms "urban" and "city" as they are also often used interchangeably. Hence, for the Web of Science search, the keywords included were "indicator*, "index", "indices", "urban", "cit*", and "sustain*" (see Supplementary Material S1 for search queries), yielding a total of 725 results as of January 26, 2023. Among the results, the review "Indicators for urban sustainability: Key lessons from a systematic analysis of 67 measurement initiatives" by Merino-Saum et al. (2020) appeared. The therein-considered 67 indicator sets and frameworks were also collected if retrievable and fulfilling the selection criteria. This led to an additional 30 academic documents and 26 non-academic documents (excluding duplicates). In total, 742 academic documents were identified. Non-academic documents were identified in a more explorative and less structured way using the results by Merino-Saum et al. (2020), the Google search engine, and the snowball sampling method. For the Google search engine, the same search words as for the search on bibliographic databases were used, and the selection criteria (published from 2010 onwards and written in English) were applied. To ensure equal representation of academic and non-academic initiatives, the number of eligible non-academic documents selected was determined a posteriori in accordance with the number of eligible academic documents (Section 2.2).

2.1.2. Collection of CACC indicator sets

The process of the review of CACC indicator sets and frameworks was performed similarly to the one of SUD indicator sets. We chose two search engines to extend the results. We included the search term "adapt" with no further specification on coastal adaptation and adaptation to rising sea levels. For CACC literature, we carried out an expanded search of indicator studies in the field of adaptation. We decided on a manual screening of the results as we noticed that indicator frameworks often address multiple hazards (e.g., heat, flood, and droughts). We extracted the indicator sets that met the scope of our study (i.e., adaptation to sea-level rise and coastal flooding). Using the keywords "indicator*, "index", "indices", "urban", "cit*", and "adapt*" (see Supplementary Material S1 for search queries) yielded 188 results for the search on Web of Science (as of Jan 26, 2023) and 223 results for the search in Scopus (as of January 26, 2023). In total, 272 distinct academic documents (excluding duplicates) were identified.

As for the review of SUD indicator sets and frameworks, non-academic indicator sets and frameworks for CACC were identified in a more explorative and less structured way using the Google search engine, the above-stated search words for the bibliographic databases, and search criteria.

2.2. Selection of indicator sets and frameworks

The selection of indicator sets and frameworks was guided by five eligibility criteria: (1) accessibility, (2) focus on sustainability/coastal adaptation, (3) city scale, (4) developed countries, and (5) applicability (Table 1).

Thus, indicator sets and frameworks must be retrievable (criterion 1), and they should focus on coastal adaptation and sustainability (criterion 2). We select indicators applied at a city scale (criterion 3), as cities are seen as critical administrative entities tackling complex sustainability, development, and planning challenges seen as drivers for change (Klopp and Petretta, 2017; Rosenzweig et al., 2018). Furthermore, climate impacts on coastal areas depend strongly on local specificities (such as topography, economic structure, and adaptive capacities) that, in turn, determine local vulnerabilities (Arnott et al., 2016; Salehi et al., 2019). Thus, assessments of adaptation strategies and their contribution to sustainable urban development need to be carried out at the city scale (Hallegatte et al., 2011; Sethamo and Harder, 2021).

Furthermore, we focus on the review of assessment frameworks for developed countries (criterion 4), as developed and developing countries face different sustainability challenges (i.a., inter alia, access to finance, lack of basic facilities, infrastructure, land ownership structure, and technical support) and dissimilar priorities including sustainable development (Feldmeyer et al., 2019; Goyal et al., 2013). The outcome of the analysis is likely to be affected by this framing (Kamble and Bahadure, 2020; Sharifi, 2013), and hence we have restricted ourselves to only developed countries.

Due to differences between individual practices and local contexts, various indicators have been applied in diverse ways (Shen et al., 2011). With the fifth criterion, we focus exclusively on indicator sets that have been applied in real-life contexts to ensure applicability and identify a shared and manageable set of core indicators applicable to different local contexts.

2.2.1. Selection of SUD indicator sets

The eligibility criteria listed in Table 1 were applied to the collected 742 academic documents of indicators for SUD, leading to 30 eligible academic indicator sets and frameworks. Using the result of Merino-Saum et al. (2020), the Google search engine, and the snowball sampling method, another 30 indicator sets from non-academic sources were included received from. Therefore, a total of 60 indicator sets and frameworks (see Supplementary Material S2 for a list of references of

Table 1
Eligibility criteria for the selection of non-academic and academic indicator sets and frameworks for sustainable urban development (SUD) and coastal adaptation to climate change (CACC).

Eligibility criteria	Description
(1) Accessibility	Source document provides accessible indicator set
(2) a Focus on sustainability	Indicator sets for SUD must cover aspects of environment, economy, and society (*three dimensions of sustainability)*
(2) b Focus on coastal adaptation	Indicator sets for CACC must focus on the adaptation to rising sea levels or other climate-related coastal impacts, such as severe storm surges as well as corresponding changes in flood risks (IPCC, 2022)
(3) City scale*	Indicator sets must be applied to a city scale
(4) Developed countries	Focus on developed countries (as classified according to UN, 2020)
(5) Applicability**	Application of indicator sets in a real-life context to one or more case studies

* Note that varying sizes of cities are not considered and vary considerably between ca. 170,000 inhabitants in Pitesti (Romania) and greater than 8 million in New York City (United States).

** Applies only to the review of SUD indicator sets.

considered measurement initiatives).totaling ca. 2,700 indicators for SUD (including duplicates) and ca. 1,500 unique indicators (see Supplementary Material S6) were reviewed.

2.2.2. Selection of CACC indicator sets

In selecting CACC indicator sets, we included those not meeting the eligibility criterion of *applicability* (Table 1), as more than 40% of academic documents did not apply their assessment frameworks to real-life case studies. (In contrast, more than 95% of SUD indicator sets in academia fulfilled the *applicability criterion*.).

The screening of collected indicator sets led to 14 eligible academic documents. As for SUD, the number of non-academic documents was determined in accordance with the number of academic documents. We identified additional 14 non-academic indicator sets using the Google search engine and snowball sampling method. In total, 28 indicator sets (see Supplementary Material S3 for a list of references of considered measurement initiatives) comprising more than 1,800 indicators for CACC were considered eligible and selected for the review process, including ca. 950 unique indicators (see Supplementary Material S7).

2.3. Screening of framework structures of indicator sets

Different indicator sets are organized following different framework structures. We screened the selected indicator frameworks and extracted the most occurring structures (steps 3.a) - d) in Fig. 1, part B). We utilized the most occurring framework structure for classifying extracted indicators (step 4 in Fig. 1, part A).

2.4. Extraction and structuring of indicators

In this study, we understand indicators as measurable constructs that can be described in specific terms (as of size, amount, duration, or mass) and are therefore quantifiable. Indicator constructs can be composed of different elements, of which the most pertinent are: an indicator label or title (e.g., impervious surfaces), a unit of measurement (e.g., percentages), a definition (e.g., percent of urban area that is impervious surfaces), accessible data, and a reference point or benchmark (Merino-Saum et al., 2020). In the extraction process, the selected indicator sets were screened for indicator labels or titles that are identical in their wording or meaning (step 4.a) in Fig. 1, part C). In an iterative process, we extracted indicators that are labeled identically or similarly (steps 4.b) and 4.c) in Fig. 1, part C). (Examples of similar indicator labels are, e.g., *water consumption/water use* and *green area/green space*.). To avoid ambiguity, a more thorough screening of underlying indicator definitions was carried out (step 4.d) in Fig. 1, part C). In other words, we differentiated between indicators that are similar in their label wording but describe different quantities and vice versa. Only indicators that describe the same quantity were grouped together. For example, two indicators labeled *water quality* may not necessarily have the same meaning. While one may focus on, e.g., water quality of drinking water, the other one may focus on, e.g., water quality of water bodies. The reverse case also applies: Two indicators describing similar quantities may appear in different wordings such as, e.g., *water quality* and *water pollution* or *green areas proximity* and *citizens' access to green areas*. In our final selection, we included indicators appearing in at least 20% of the collected frameworks (step 4.e) in Fig. 1, part C) to extract widely applicable indicators and to avoid long, extensive sets.

All extracted indicators were classified into the selected framework structure (step 3.d) in Fig. 1, part B). Some indicators may be attributed to various categories (e.g., sustainability dimensions and subordinate themes) across different frameworks. We extracted all categories attributed to the indicators in the different frameworks. Indicators were organized into distinct categories based on consistency in literature or in a way that accommodated the overall logic of the framework structure.

2.5. Consolidation of indicator frameworks

In the last step (step 5 in Fig. 1, part A), we consolidated the results and findings. *Consolidation* is understood as systematically comparing and integrating results. This can pave the way for integrated assessments and decision support in coastal adaptation planning under the paradigm of sustainable adaptation. We compare and analyze the similarities and differences between the extracted and structured dimensions, themes, and indicators. Themes and indicators originating from the SUD and CACC frameworks are identified and analyzed regarding (1) complementary objectives and (2) conflicting objectives. We considered objectives complementary if achieving one objective will also assist in meeting another objective. This is usually the case if an intended indicator trend (an increase or decrease in indicator values) can be met in both planning domains. Further, we outlined and discussed conflicting objectives as objectives that contradict each other and cannot be fully achieved at the same time.

3. Results

3.1. Structures of indicator sets

The screening of selected indicator sets and frameworks for SUD and CACC uncovered different framework structures. We determined the following four common structures:

1. *Hierarchical structure based on sustainability dimensions:* Indicators are organized in a hierarchical structure based on sustainability dimensions (i.a., environment, society, economy) (see Fig. 2, part B)
2. *Hierarchical structure based on other dimensions:* Indicators are organized in a hierarchical structure based on other dimensions (e.g., vulnerability dimensions, resilience dimensions)
3. *No structure (*i.e.*, indicator sets):* Indicators are not organized in a framework structure
4. *Complex framework structures*: Combination of different structures (e.g., integration of more than one set of dimensions) (see Fig. 2, part C)

3.1.1. Structures of indicator sets for SUD

Most SUD frameworks follow hierarchical structures based on sustainability dimensions (Fig. 2, part A) that can be divided into two-level hierarchical structures (Rajaonson and Tanguay, 2019) and multi-level structures (Shen et al., 2011). In addition to a dimension and an indicator level, multi-level structures include one or more additional levels of classification, such as themes (Fig. 2, part B). Several frameworks do not explicitly suggest a classification into sustainability dimensions but follow a two-level theme-based structure (e.g., *energy, health, economic development)* (e.g., Haider et al., 2018; Moussiopoulos et al., 2010). Among the reviewed frameworks, the characteristics and purposes of themes may vary from one indicator framework to the other but commonly refer to thematic areas or sectors assessing similar development objectives. Indicator frameworks from academic initiatives appear to select broader themes such as e.g*., air, health, and economic development* (Shen et al., 2011; Zoeteman et al., 2015). Several indicator frameworks by non-academic measurement initiatives replace themes with more concrete urban development objectives or issues of policy relevance, such as e.g., *natural land protection, active and healthy citizens, community connectedness, economic activity, diversity, and prosperity* (City of Issaquah, 2016; Patridge et al., 2011). A few frameworks introduce themes for the purpose of developing aggregated indices for thematic areas (Alfaro-Navarro et al., 2017; Rodrigues and Franco, 2019).

Four out of 50 measurement initiatives suggest indicator sets that are not anchored in any kind of framework structure (Fig. 2, part A). Lastly, two frameworks for SUD introduce a more complex structure. Munier (2011) suggests not only classifying indicators for SUD into sustainability dimensions but also linking indicators to concrete sustainability

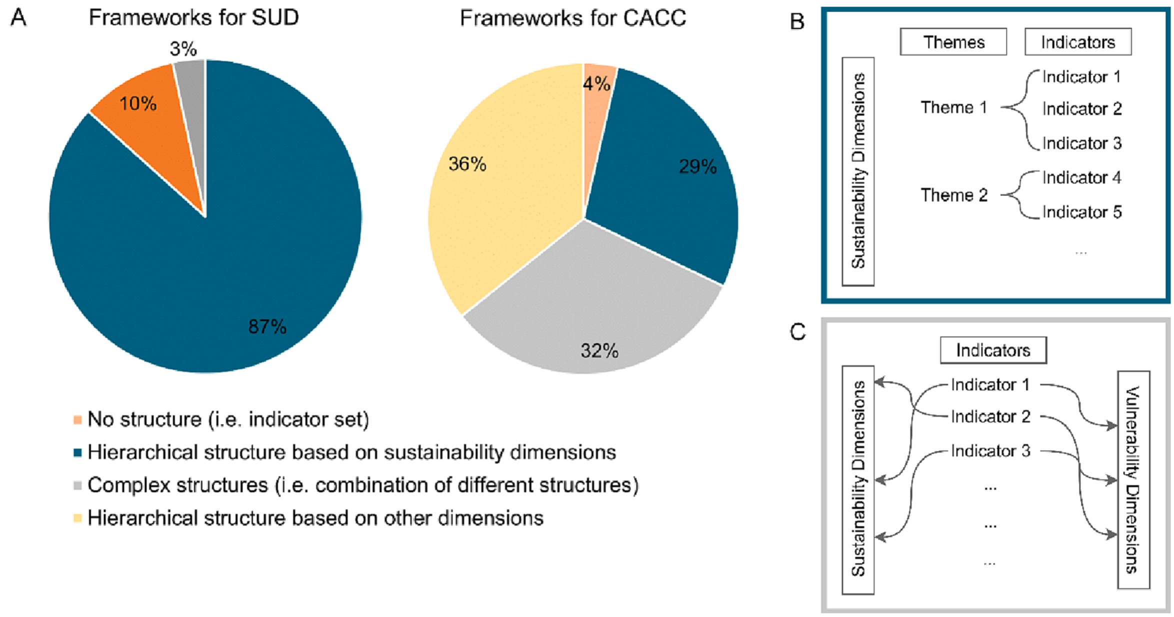

Fig. 2. A: Percentage distribution of framework structures for SUD and CACC; B: Example of a hierarchical structure based on sustainability dimensions (e.g., Shen et al. (2011)); C: Example of a complex structure for CACC (e.g., Bigi et al. (2021)) (see online version for color representation).

targets lying at the interface between different sustainability dimensions. Shmelev & Shmeleva (2018) explore linkages between different sustainability dimensions and indicators.

3.1.2. Structures of indicator sets for CACC

As for frameworks for SUD, most frameworks for CACC are based on a hierarchical structure (Fig. 2, part A). However, only 29% are based on sustainability dimensions, and 36% of hierarchical frameworks include other dimensions, of which the most occurring are related to vulnerability components (Bigi et al., 2021; ND-GAIN, 2018) or a mix of vulnerability and sustainability dimensions (City of Surrey, 2013). The review uncovered that the following four vulnerability components are most represented among the selected frameworks: impact, exposure, sensitivity, and adaptive capacity, which are commonly defined as determinants of vulnerability (IPCC, 2012). Some indicator frameworks integrate *input-process-output-outcome structures* along vulnerability dimensions and sustainability dimensions (Figueiredo et al., 2018; Institute for Sustainable Communities and Urban Sustainability Directors Network, 2016).

Several frameworks for CACC introduce themes as a classification level (Feldmeyer et al., 2019; Sharifi and Yamagata, 2016). As for SUD, academic initiatives for CACC tend to select sector-oriented themes such as e.g., water, energy, and healthcare. Non-academic measurement initiatives often associate themes with urban development objectives such as e.g., *equitable access to safe and secure water supply, availability of natural resources, and promoting adaptive infrastructure* (Figueiredo et al., 2018; Rogers et al., 2020).

A considerable share of 32% of frameworks for CACC follows a more complex structure refraining from classical hierarchical structures by integrating different dimensions (Fig. 2, part C). Several frameworks integrate vulnerability dimensions and sustainability dimensions (Balica et al., 2012; Giannakidou et al., 2019; Swart et al., 2012; Tapia et al., 2017). Suárez et al. (2016) developed an Urban Resilience Index that is based on an integration of "core urban resilience factors" (i.e., *diversity, modularity, tightness of feedback, social cohesion*, and *innovation*), indicators, and their influence on each other. Lastly, one out of 28 indicator sets is not anchored in a framework but used for an index-based approach to enable the integrated assessment of city resilience in flooding scenarios (Barreiro et al., 2021).

3.2. Extraction and structuring of indicators

As three-level hierarchical structures (Section 3.1) occur most frequently in literature, we chose this framework structure for the classification of extracted indicators. We applied similar structures for the SUD and CACC frameworks to facilitate comparison. At a top level, we included the widely accepted three dimensions of sustainability (environment, economy, and society) and two additional dimensions (governance and built environment & infrastructure) that frequently occur in literature (Fig. 3). At the second level of the framework structure, we determined themes based on consistency in literature or in a way that accommodated the overall logic of the framework structure. In other words, most occurring themes linked to the extracted indicators were adopted. In cases of ambiguities, the indicators were grouped into already existing themes. Level three is represented by the extracted indicator labels and units. There are terminological ambiguities that became apparent during the extraction process and that need to be mentioned: While we required indicators to be measurable (Section 2.4), some of the reviewed frameworks did not include this requirement. Other studies may define what we consider a theme as an indicator.

(More extracted information on indicator elements, such as more detailed definitions of measurements or methods of calculations, can be found in Supplementary Materials S4 and S5.).

3.2.1. Indicator framework for SUD

The screening of selected indicator sets and framework resulted in 44 extracted indicators for SUD (Fig. 1, part C). In comparison, the average number of indicators among the reviewed indicator sets is 45 (ranging from 8 to 181). Fig. 4 shows the resulting three-level hierarchical framework for the extracted indicators for SUD. The five addressed dimensions are subdivided into 18 themes that contain one or more indicator(s). There is consistency in the literature for most dimensions, themes, and associated indicators. For example, most frameworks associate the indicator *share of renewable energy* with the theme *energy* and the environment dimension or the indicator *life expectancy* in the theme *health* and the social dimension. (For details on the structuring process, see Supplementary Material S8.).

It is important to note that the number of extracted indicators is sensitive to the selection criterion. Decreasing the minimum occurrence of indicators in reviewed sets from 20% to 15% would lead to 12

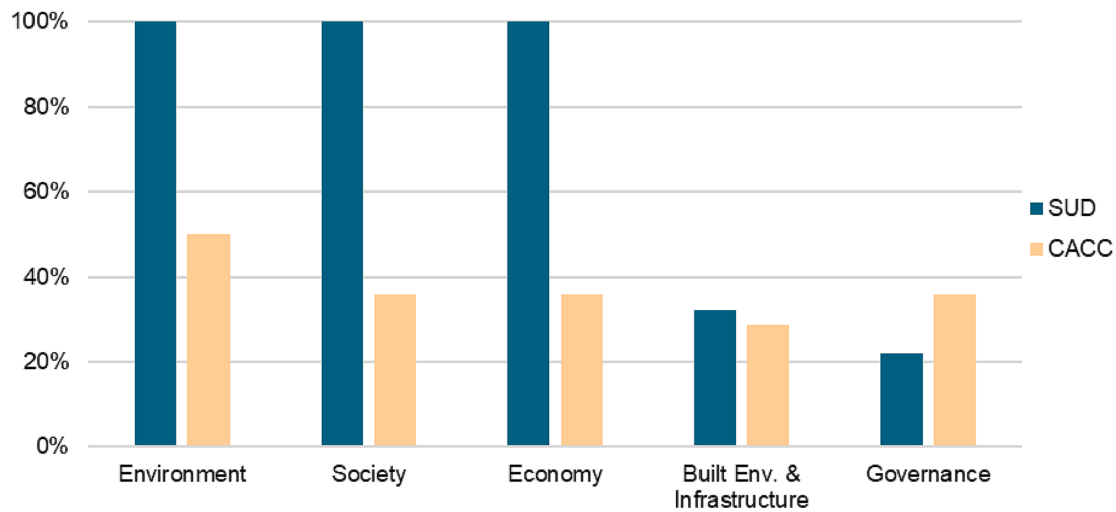

Fig. 3. Frequency of occurrence of five dimensions (environment, society, economy, built environment & infrastructure, and governance) among indicator sets for SUD and CACC.

additional indicators covering all five dimensions of the framework for SUD (Fig. 4). Including only indicators that appear in at least 25% of the frameworks would result in the removal of 15 indicators across all five dimensions. By sticking with a threshold of 20%, we extracted a manageable and widely applicable set of indicators.

In addition to the three-level framework structure, Fig. 4 also provides information on how often the indicators occur among the reviewed indicator sets. Only two indicators were found in more than half of the sets (*water consumption* and *unemployment rate*), and only 15 indicators were found in more than one-third of the sets. Among these 195 indicators, only the three dimensions of sustainability (i.e., environment, society, and economy) are covered, with the environmental and social dimensions being most strongly represented. This demonstrates the importance of sustainability dimensions with a strong focus on society and the environment. Overall, more than three-thirds of all 44 indicators are either within the environmental or social dimension.

3.2.2. Indicator framework for CACC

For CACC, the screening of selected indicator sets and frameworks resulted in 36 extracted indicators (Fig. 1, part C). In comparison, the average number of indicators among the reviewed indicator sets is 65 (ranging from 5 to 249). As for SUD, the number of extracted indicators varies with the selection criterion. Decreasing or increasing the minimum occurrence of indicators in reviewed sets by 5% would lead to 15 additional indicators or reduce the set by seven indicators, respectively.

As discussed in Section 3.1.2, only 29% of the reviewed frameworks are based on sustainability dimensions or extensions thereof, and 36% include other dimensions, of which the most occurring are related to vulnerability components (Fig. 2, part A). Fig. 5 represents a three-level framework for the extracted indicators for CACC utilizing the aforementioned four vulnerability components (i.e., impact, exposure, sensitivity, and adaptive capacity) as higher-level dimensions. The second level represents 15 themes encompassing one or more indicator(s). While most dimensions and associated indicators coincide, there is little consensus on themes in the literature. To develop a theme-based structure, we selected themes considering existing themes in the literature that best accommodate the causal structuring of indicators (For details on the structuring process, see Supplementary Material S9). In Fig. 5, the themes are colored, relating to the five dimensions (i.e., environment, society, economy, built environment & infrastructure, and governance) to illustrate the link between frameworks. Almost two-thirds of the indicators are within the dimension of adaptive capacity, encompassing most of the indicators within the built environment and infrastructure, and governance.

Considering the occurrence of indicators, only one indicator (*urban green areas*) appeared in more than half of the sets. Only three indicators (*urban green areas, citizen awareness on climate-related topics,* and *impervious surfaces*) were found in more than one-third of the sets, demonstrating great conceptual inconsistencies among different frameworks for CACC. These inconsistencies are reflected in significant differences in the sizes of indicator sets. Additionally, the five largest sets cover half of the total number of indicators for CACC reviewed in this study.

To provide comparability and coherence, we introduce an alternative structuring of indicators for CACC based on the five dimensions of environment, society, economy, built environment & infrastructure, and governance (Fig. 6). The 36 indicators are almost equally distributed across all dimensions, with the social and environmental dimensions being slightly more represented.

3.3. Consolidation of indicator frameworks

The last part of our results analyzes the third research question on how the two planning domains interact in their assessments, addressing (1) complementary and (2) conflicting objectives (see Section 2.5). In Fig. 7, we visualized the situations where we identified shared, complementary and conflicting objectives of SUD and CACC at the themes level. The matrix (Fig. 7) can be interpreted bi-directionally, meaning that achieving an objective of SUD will assist in (complementary objectives) or inhibit (conflicts) meeting an objective of CACC and vice versa. The following subsections will discuss these interactions in more detail.

3.3.1. Shared themes and indicators of SUD and CACC

The frameworks for SUD and CACC include several shared indicators and themes (Fig. 7). In Fig. 7, themes that typically entail shared or complementary objectives are highlighted in light grey and are elaborated below. In some cases (e.g., urban form and population), shared indicators and themes relate to conflicting objectives, as discussed in Section 3.3.3.

Both frameworks cover economic themes. While SUD considers economic indicators with a focus on a “high standard of living”, CACC focuses on the capacity of a city to protect itself against, withstand and rebuild after floods. For example, *median household income* is applied in both frameworks but with different interpretations (Brooks et al., 2005; Figueiredo et al., 2018; UN-Habitat, 2016). Both aspects go hand in hand. While not applying the same indicators and themes, both SUD and CACC frameworks thus aim to quantify the same objectives.

Both frameworks consider impacts on environmental quality. This is

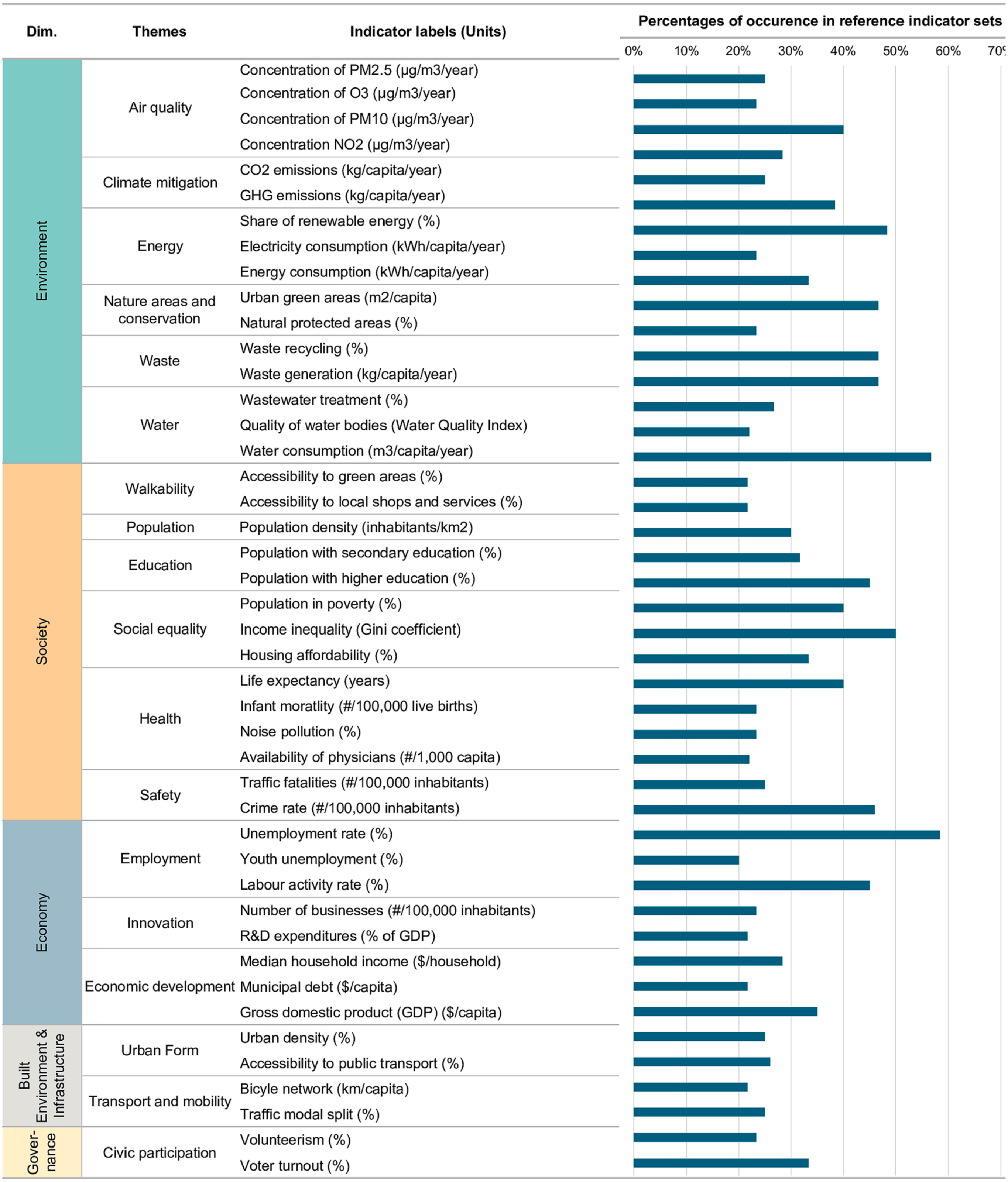

Fig. 4. Indicator framework of most frequent SUD indicators (44#) including the percentage of indicator sets and frameworks (≥20%) in which they appear; Framework structure based on higher-level dimensions (Dim.) and themes.

expressed in consideration of air quality as well as their emphasis on the availability of urban green areas. For the latter, both frameworks consider nature conservation aspects, while SUD typically has an additional focus on providing recreational spaces (Braulio-Gonzalo et al., 2015; Marín Cots et al., 2012), where CACC seeks opportunities for retaining water (City of Surrey, 2013; ICLEI Canada and CAP 2015; Swart et al., 2012). These objectives are readily combined, and stakeholders in modern water management are usually aware of both needs.

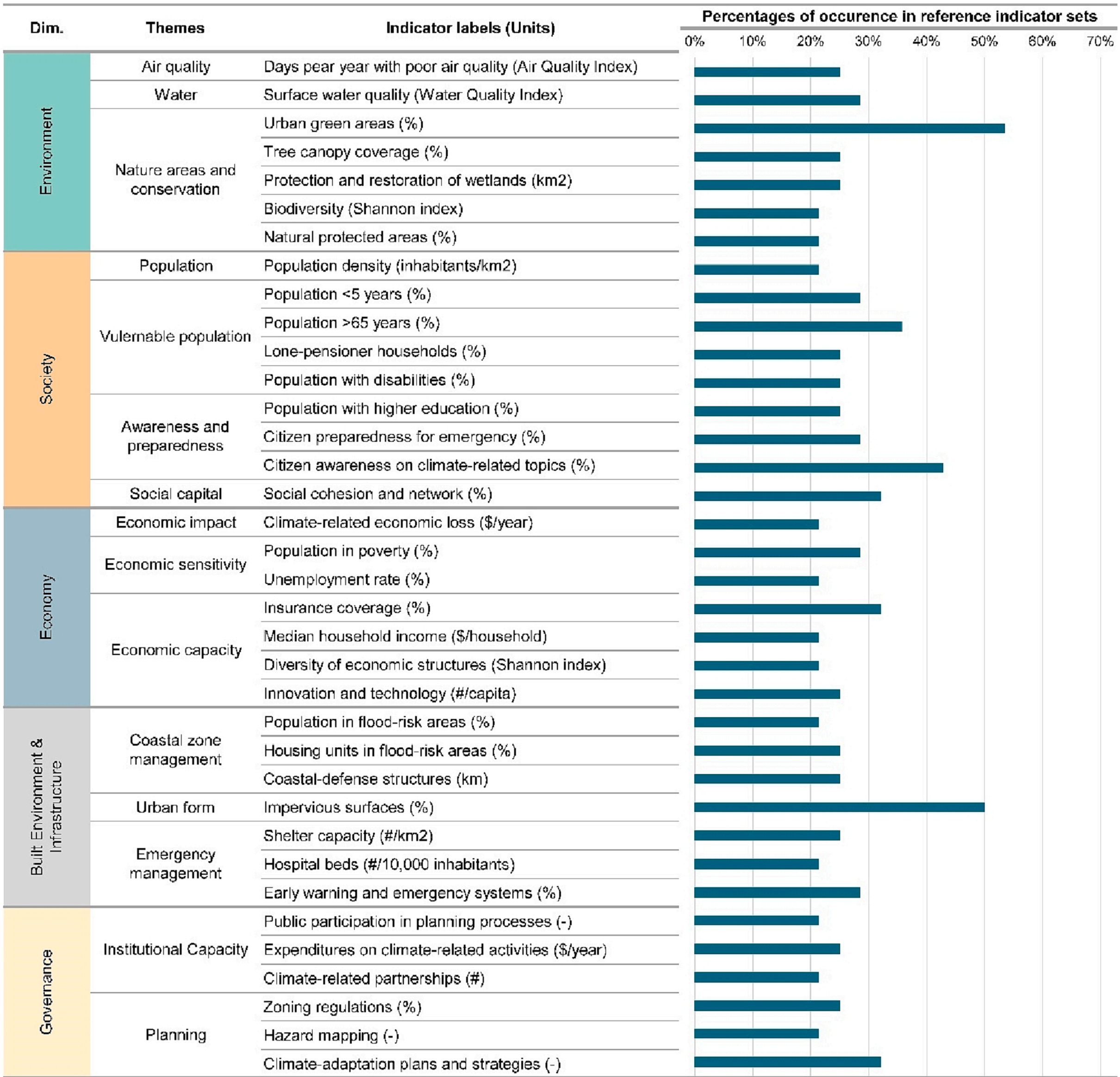

Fig. 5. Indicator framework of most frequent CACC indicators (36#) including the percentage of indicator sets and frameworks (≥20%) in which they appear; Framework structure based on higher-level vulnerability dimensions (Vulnerab. Dim.) and themes (see online version for color representation).

We, therefore, concluded that the frameworks overlap in these aspects.

3.3.2. *Complementary objectives of SUD and CACC*

Aside from shared themes and indicators, most complementary objectives occur in the social dimension and few across the other four dimensions (Fig. 7).

For example, *Social equality* in SUD can have a positive effect on reducing disparities in the citizens' *Awareness and preparedness,* e.g., private precautionary disaster preparedness (i.e.., installation of protective water barriers, structural changes to the home, or rearranging furniture) increases with economic capacities (Grothmann and Reusswig, 2006; Shah et al., 2020). Citizens' *Awareness and preparedness* affect, in turn, positively *Health* (in SUD).

Awareness and preparedness may also be fostered by *Civic participation* in the SUD framework (Burningham et al., 2008; Haski-Leventhal et al., 2010; Venghaus et al., 2022; Wachinger et al., 2013). Civic participation, in turn, plays an important role in achieving democratic practices, legitimate decisions, and the accountability of governments (Patridge et al., 2011; Global Platform for Sustainable Cities, 2018; UN-Habitat, 2016). These are crucial factors for building Institutional capacity (in CACC), including common acceptance and ownership of planning decisions and, eventually, the uptake of adaptation measures (Roca and Villares, 2012; Storbjörk and Hedrén, 2011).

The theme of *Education* in SUD strives for high education levels to increase social well-being and economic development (Akande et al., 2019; UN-Habitat, 2016). CACC, on the other hand, aims to secure *Awareness and preparedness* against flood hazards. Higher education levels may reflect citizens' awareness of the climate change problem and suggest their openness to various adaptation solutions (Figueiredo et al., 2018; ND-GAIN, 2018; Swart et al., 2012). However, literature argues that there is no significant causal relationship between risk awareness and disaster preparedness (Lieske et al., 2014; Scolobig et al., 2012). Higher education levels can yet, be seen as a proxy for Economic capacity and, thus, recovery capacity (Figueiredo et al., 2018; ND-GAIN, 2018).

3.3.3. *Conflicting objectives of SUD and CACC*

The great majority of conflicts occur across the dimensions of built environment & infrastructure and governance, most of which are related to assessments of *Urban form*, *Coastal zone management,* and (coastal

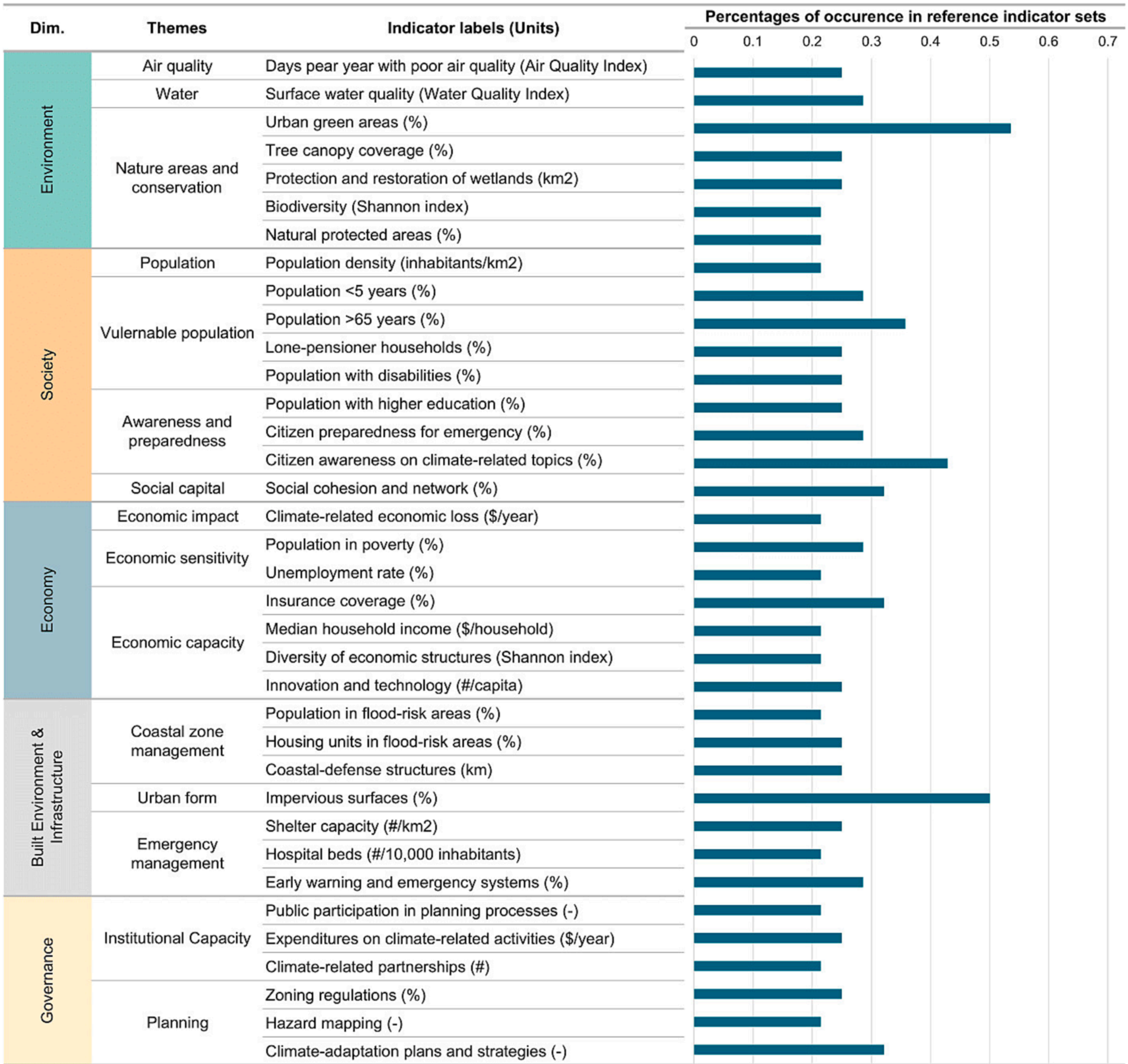

Fig. 6. Indicator framework of most frequent CACC indicators (36#) including the percentage of indicator sets and frameworks (≥20%) in which they appear; Framework structure based on higher-level dimensions (Dim.) and themes.

adaptation) *Planning* (Fig. 7).

In frameworks for SUD, the assessment of *urban form* commonly relates to land-use reduction through urban density (to reduce the environmental impact), addressing objectives of walkability, reducing motor traffic but also economic gain (Alpopi et al., 2011; Frick and Rodríguez-Pose, 2018; Marín Cots et al., 2012). In CACC, *Urban form* primarily assesses the sensitivity of developed urban areas, as impervious surfaces increase surface water runoff and exacerbate flooding (ND-GAIN, 2018; Swart et al., 2012). The assessments of *Urban form* in SUD and *Coastal zone management* in CACC create conflicting objectives, as SUD fosters an increase in urban density (as well as population density) that can lead to an increase in flood exposure, at least in flood-prone areas of the city. (Bigi et al., 2021; Covenant of Mayors for Climate & Energy Europe, 2016). Thus, conflicts may arise if spatiotemporal impacts are ignored.

Conflicts can also arise if CACC ignores the assessment of *Social equality*. For example, an increasing share of coastal housing units will be vulnerable to flooding in the coming decades, which will result in higher prices for homes that are not vulnerable to flooding (Mitch, 2022). Thus, adaptation strategies must address housing affordability that comes along with equity concerns but also economic challenges (Buchanan et al., 2020).

As another area of conflict, the malintegration of climate mitigation and adaptation has frequently been discussed in the literature (Howells et al., 2013; Sharifi, 2021; Tol, 2005). Frameworks for CACC ignore assessments of *Climate mitigation* included in SUD assessments (Fig. 7). Conflicts may occur when adaptation measures require high energy demand or entail emissions through material consumption and the destruction of ecosystems (Grafakos et al., 2018). In particular, hard engineering structures such as levees and dikes can require high energy demand or entail emissions through material consumption and destruction of ecosystems (Ibid.).

4. Discussion

4.1. Differences in framings and conceptualizations

The variety of framework structures reflects the ambiguity of how the planning domains of SUD and CACC are understood and

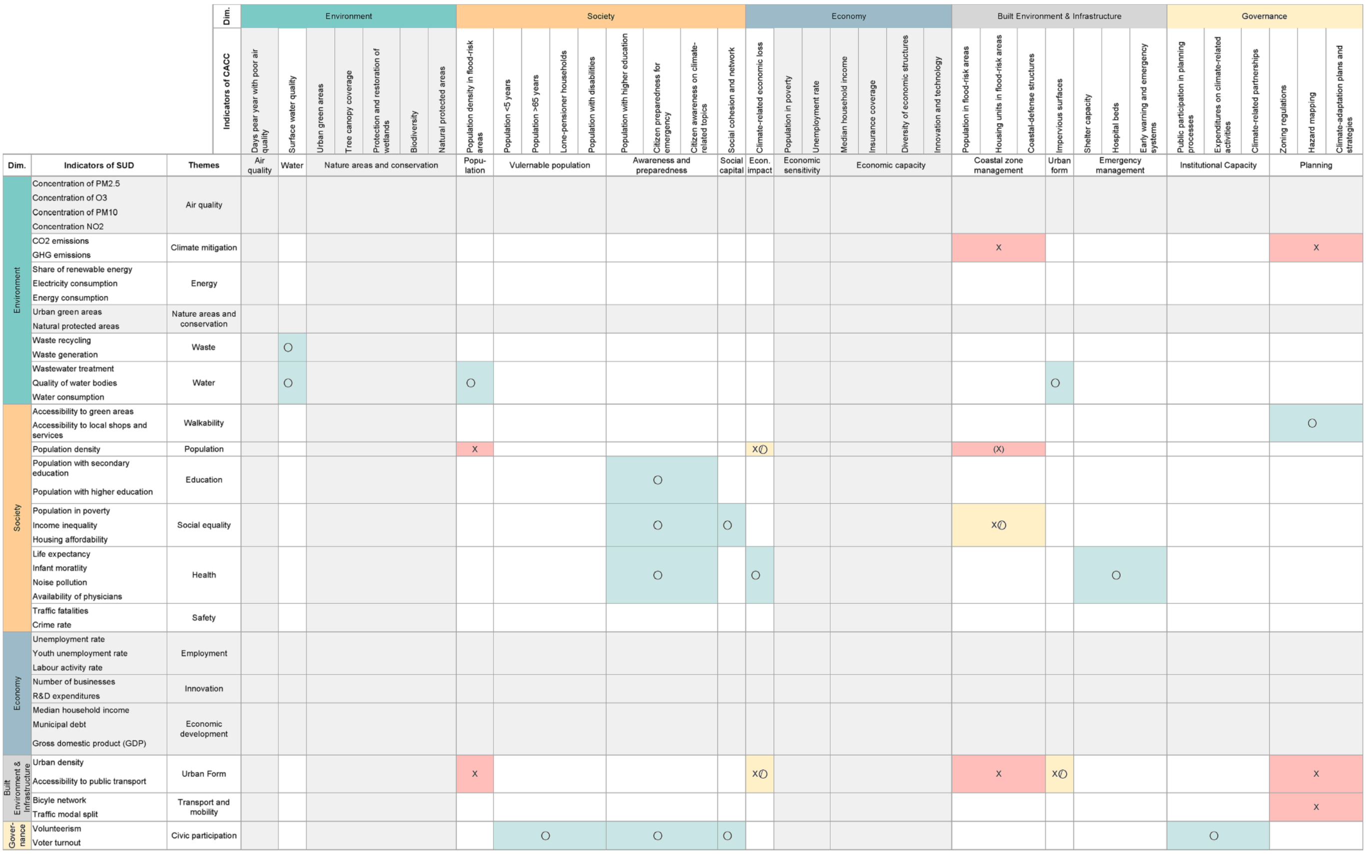

Fig. 7. Complementary (○) and conflicting (x) objectives and CACC across themes and dimensions. Common themes with shared objectives are highlighted in light grey (see online version for color representation).

operationalized. The wide range of indicator sets and frameworks can be explained by, inter alia, the absence of agreed targets, local differences in geography, economy, political condition, differing perspectives, and discourses on sustainability visions. These disparities are reflected by the different indicator sets and frameworks varying considerably regarding, e.g., the number of indicators, addressed framework structures, and purposes. Ambiguities are also reflected by the sensitivity of indicator occurrence to the selection threshold. Rather than a core set of indicators, many different indicators are widely used in both domains of SUD and CACC.

While different conceptualizations of SUD have developed into a consistent paradigm considering framework structures and dimensions, frameworks for CACC lack this consistency; one reason may be the plurality of concepts underlying CACC assessments (i.e., adaptation, resilience, and vulnerability) and the lack of clear-cut definitions used by scientists and practitioners (Vogel et al., 2007). Further, different disciplinary fields try to frame CACC in different directions with different attributes, spatiotemporal framings (influenced by spatiotemporal uncertainties of climate impacts), and different goals (Klostermann et al., 2015; O'Brien et al., 2007). This inhibits the translation from science to practice, which is reflected by the lack of application of CACC frameworks in a real-life context.

At the indicator level, CACC assessments define and use fixed spatial land-use allocation, whereas indicators for SUD are less spatially constrained. This may be due to CACC incorporating vulnerability assessments that are spatially explicit (e.g., *population in risk areas* or *coastal defense structures*), while SUD assessments often include drivers of urban development using a spatial mean (e.g., *urban density* or *life expectancy*). However, indicators of both planning domains ignore the temporal impacts of vulnerability. For example, coastal defense structures may promote the short-term interest in urban development characterized by perceived long-term societal benefits (e.g., increased housing availability or employment). Ignoring long-term flood risk management may eventually lead to an increase in the risk of damage (EEA, 2020).

4.2. Conceptual barriers to integrated assessments

Identified conflicting objectives (Fig. 7) originate in different scopes of city functions. As mentioned above, CACC tends to focus on concrete spatially explicit adaptation measures, ignoring wider impacts on socioeconomic systems, while assessments of SUD consider the city and its functions as a whole (Santos et al., 2002). Further, it becomes clear that SUD ignores vulnerability assessments, and most indicators do not cover the vulnerability dimensions addressed by CACC. In particular, it is noteworthy that the two most important themes across all CACC frameworks, i.e., climate-related economic loss and emergency management, have no connection to the SUD themes at all. The analysis shows that SUD widely ignores risk, uncertainty, and the probability of socioeconomic shocks. CACC, on the other hand, accounts for risk but ignores many aspects of the traditional three pillars of sustainability. Together with the ambiguity in the framing of the CACC indicators, it is perhaps difficult for users of SUD frameworks to perceive risk as an important driver for urban land use allocation.

Potential conflicts between SUD and CACC may be resolved by careful planning, but not without compromising the optimal solution within each of the planning domains. Compromising optimal solutions within SUD and CACC by integrating assessments of the two planning domains may, however, lead to more sustainable and resilient pathways. Furthermore, developing integrated strategies facilitate complementary objectives of SUD and CACC, and cross-sectoral synergies can be harvested, leading to more robust decision-making.

4.3. Limitations and further research

We selected indicator sets and frameworks with a focus on cities. However, the sizes of cities vary considerably (between ca. 170,000 and greater than 8 million inhabitants), entailing context specificities and diverse needs. Context specificities can be formed by, e.g., demographic characteristics and different economic interests but also differences in hazard risks and vulnerability (Figueiredo et al., 2018). The developed frameworks in this study are based on a set of core indicators widely applicable but ignore context-specific indicators. This method kept indicator sets below a certain size and allowed for a general comparison of the planning domains of SUD and CACC.

When identifying complementary and conflicting objectives, we regarded indicators independently and ignored more complex causal relationships among indicators (Fig. 7). Yet, it is important to point out that most indicators represent processes that are strongly linked (Munier, 2011; Tran, 2015). Considering *cause-effect* relationships may uncover more complementary objectives or conflicts.

We have highlighted some barriers and potentials of integrated assessments of SUD and CACC, which might serve as a basis for further work on science and implementation. For further development of an integrated framework, we suggest the following four key recommendations:

- The ambiguities in the framings of CACC assessments must be tackled. We suggest two possible ways forward: either to develop a mature CACC framework along sustainability dimensions or to accept a complex framework structure where SUD also is mapped along vulnerability
- The interplay between dimensions, themes, and indicators should be extended to include cause-effect relationships to allow dynamic assessments of future development.
- A framework for assessing specific actions must be applied to the relevant context in terms of the spatial and temporal scales at which the indicators and themes operate.
- Most conflicts between CACC and SUD occur in the dimension of built environment and infrastructure, involving an implicit *fight for space*. To avoid unintended trade-offs and negative outcomes, principles for *robust* land-use allocation that adheres to both planning domains are needed. The analysis shows that there are large synergies to be harvested if CACC and SUD strategies are developed concurrently.

5 Conclusions

We reviewed existing literature on indicators for SUD and CACC comprising 2,200 and 1,800 indicators, respectively. The review uncovered a multitude of framings and conceptualizations of the two domains. At a structural level, SUD frameworks are close to being consistent in their framing and follow a hierarchical structure based on sustainability dimensions. Frameworks for CACC differ widely in their conceptualization in that they do not stipulate whether to build upon hierarchical or complex structures and which dimensions to incorporate. Also, at the detailed, measurable indicator level, frameworks for CACC demonstrate greater conceptual inconsistencies and little agreement on a core set of indicators.

After systematically analyzing the frameworks for SUD and CACC, we identified a remarkable lack of overlap between the planning domains, both when considering actual measurable indicators and when aggregating these indicators to a higher level. This is expected to be due to the above-mentioned ambiguities in the framings of CACC and different scopes on city functions: While CACC excludes the assessment of wider city functions affected by adaptation measures (e.g., the impact on housing affordability), SUD ignores flood vulnerability across all dimensions (e.g., the increase of population density regardless of risk areas). Further work should focus on (1) defining an agreed set of measurable indicators to operationalize shared planning objectives of SUD and CACC, (2) identifying the feedback mechanisms between planning objectives for SUD and CACC, and (3) mapping different spatial and temporal scales at which the different planning objectives apply.

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.

Data availability

All used data are shared in the Supplementary Materials.

Acknowledgments

This work was funded by Realdania through the project *Cities and Rising Sea Levels.* We would like to thank the researchers from the Aarhus School of Architecture and the University of Copenhagen who contributed to this study with valuable discussions as part of the project. Furthermore, we want to thank the employees at the department of Technology & Environment of Vejle Municipality for their important input and feedback during a workshop on indicators.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110078.

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