Research Paper

From Urban Factors to Further Impacts

Redefinition of Urban Heat Vulnerability to Face Future Challenges from Multi-sectors

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Abstract

Government agencies utilize urban heat vulnerability as a critical reference indicator for determining the need for mitigation activities. This concept has been frequently defined as the propensity of cities to incur negative impacts in response to the extremely high temperature. To face the impacts and challenges of heat vulnerability from various sectors - urban structure, building status, population, exposure, emissions, human health, and economy - a qualitative Multi-sector Causal Network (MCN) was designed to enable the application of decision-making crossing different governance departments. In this research, further quantitative analysis of the causality existing in the MCN was conducted to demonstrate the cause-effect flows, providing three levels of heat vulnerability indicators for future assessment based on the MCN. As a result, the research demonstrates that the abstract idea of urban heat vulnerability can be concretized by the outcomes it generates, which will aid urban decision-makers in the future in allocating resources more rationally to meet the requirements of diverse sectors in a balanced manner. Also, compared with other sectors, the study reveals that the economic sector has lagged in the research area of heat vulnerability, despite its importance in the network.

Keywords

Heat vulnerability, Multi-sector causal network (MCN), Emissions, Human Health, Economy

1. Introduction

As a significant indicator of the urban thermal environment, urban heat vulnerability can be represented as the sensitivity and adaptation of cities and populations to high temperatures. In the modified 6th IPCC Report, the interactions between numerous sectors, such as society, energy industry, urban/rural infrastructure, etc., are underlined in the framework of an integrated climate hazard (Pörtner et al., 2022). Urban extreme high temperature, as a vital part of hazards, also interacts with these sectors and can be mitigated and adapted through implementing strategies (Rana et al., 2022; Santamouris et al., 2020). The extremely high temperature has numerous adverse effects, including, but not limited to, ecological destruction, deterioration of human health, increased energy consumption, air pollution, decreased productivity, etc. For example, in the context of global warming, reducing high temperatures has become one of the most crucial issues resulting from releasing greenhouse gas emissions (Akimoto et al., 2018; Roxon et al., 2020). With the gradual stabilization of Covid-19, it is anticipated that the world economy will recover, leading to an increase in emissions (Cottafava et al., 2022; Ray et al., 2022). Now the research about heat vulnerability in urban areas mainly focuses on the evaluation based on superimposition and weighting of vulnerability factors. For example, in conjunction with physical and social factors based on exposure, sensitivity, and adaptation, a study in Chongqing, China, established a model of heat vulnerability to explore the distribution of heat vulnerability for urban risk management (Xiang et al., 2022). By combining high-resolution spatial information and crowdsourcing geospatial data, another study in Padova, Italy, offered indications of sensitivity, adaptive capacity, vulnerability, exposure, and risk, identifying the different heat vulnerability related to various urban typologies (Maragno et al., 2020). From past research, it can be seen that urban heat vulnerability was frequently defined as a more abstract concept that includes affected vulnerability elements (including both adaptive capacity and sensitivity) without specifying adverse impacts, making it fuzzy to apply at various levels and across multiple sectors of society.

Under such a background, a more effective network of urban heat vulnerability - Multi-Sector Causal Network (MCN) - was established, providing greater assurance in facing such formidable obstacles by authors (Yang et al., 2022). It initiated several chain reactions for cities and individuals. As a further analytical development of the MCN study, this study will focus on the quantitative analysis of the magnitude of importance of indicator nodes and cause-effect links present in the network through statistics from previous studies. With the previous MCN study, this paper will fill the gap between heat vulnerability and its causal relationships within multi-sectors. By looking at the quantitative causality flows in the network, the hierarchy of indicators in each sector will be given to guide future work on thermal vulnerability assessment. Simultaneously, state-of-the-art mitigation solutions and the new vulnerability network were merged to define the path of future deployment. The paper structure is organized as follows:

- **Quantitative analysis based on the qualitative MCN**: the basis of urban heat vulnerability redefinition, including a concise introduction of previous qualitative MCN, quantitative analysis of involved nodes and cause-effects
- **The causality from urban Factors to their impacts**: a cause-effect flow chat with three levels of heat vulnerability indicators, based on which a summary of the causality among multi-sectors redefining the urban heat vulnerability to adapt to challenges from emissions, human health, and economy, was also given, redefinition of urban heat vulnerability
- **Conclusions**: a conclusion of the paper and some recommendations for future urban heat vulnerability assessment

2. Quantitative analysis based on the qualitative MCN

2.1. Introduction of the qualitative MCN

Given that this thesis is based on the authors' proposed MCN (Multi-sector Causal Network) (Figure 1) continues to deepen the quantitative scientific evidence (Yang et al., 2022), all indicator-level causality was discussed in detail, which can be seen in the previous study. A brief review and introduction to this qualitative MCN are given here. The MCN comprises three cause sectors (building stock, urban structure, and demographic), one intermediary sector (exposure), and three effect sectors (emissions, human health, and economy). Through macroscope causal links between the seven sectors and detailed causal links between the vulnerability items within each sector, the MCN effectively extends the multi-disciplinary scope of heat vulnerability assessment, specifying how urban elements and populations exhibit heat vulnerability in each effect. At the same time, the MCN also introduces mitigation, specifying which stages of different assessment interventions can intervene in and guiding decision makers in the future governance process to choose more direct means to reduce heat vulnerability in effect-oriented cities. The purpose of the MCN is not only to broaden the knowledge of heat vulnerability assessment for current researchers, but more importantly to serve as a causal theoretical basis for the authors to further develop the multi-sector Bayesian network assessment framework in the future.

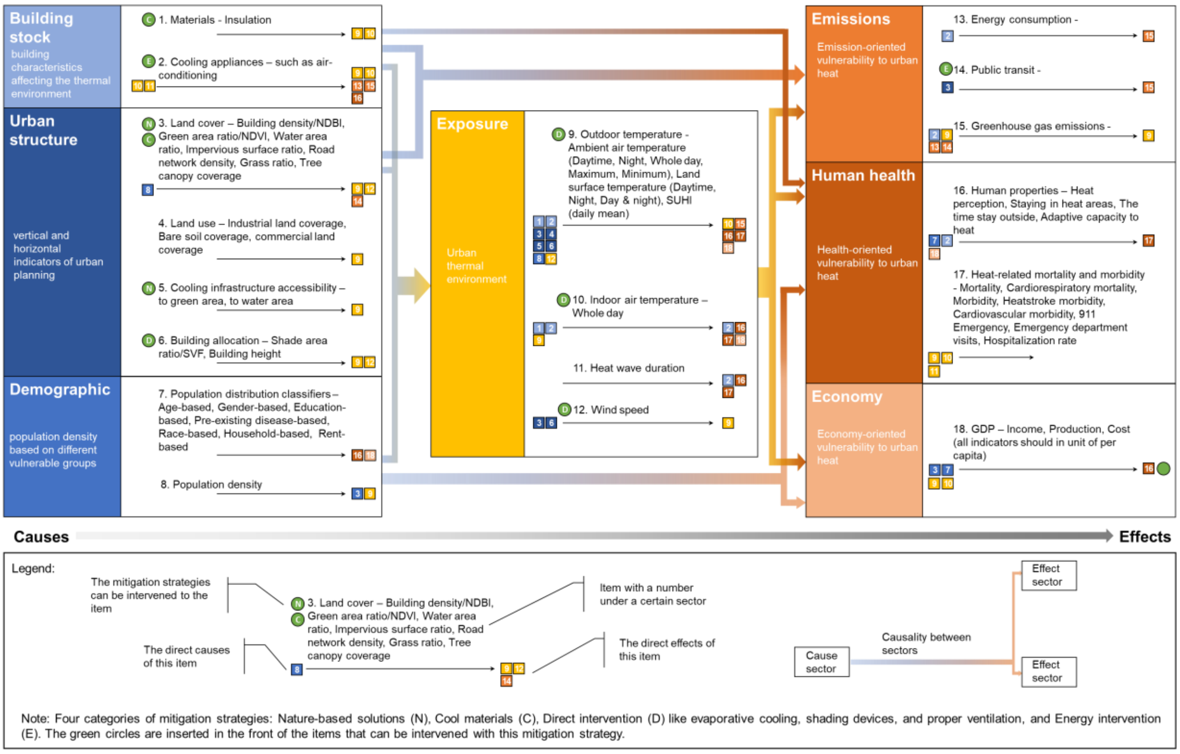

Figure 1. Multi-sector causal network (MCN) of urban heat vulnerability

The construction of the MCN involved screening 163 papers on 'urban heat vulnerability assessment' and eight additional papers on climatic economy related to high temperature. It also includes 803 sets of causal relationships that were screened and transformed by the authors into direct links based on the definition of causality and the presence of vulnerability indicators in 164 different sectors. The qualitative causal relationships present in the MCN will be analyzed together with the quantitative analysis in sections 2.2 and 2.3 of this study. Figure 2 demonstrates the quantitative causality map based on the occurrence of causality among indicators. Solid black lines indicate positive causality, dashed black lines indicate negative causality, and grey lines indicate non-linear causality. All the above scientific evidence data will be used as the basis for the quantitative analysis of this study.

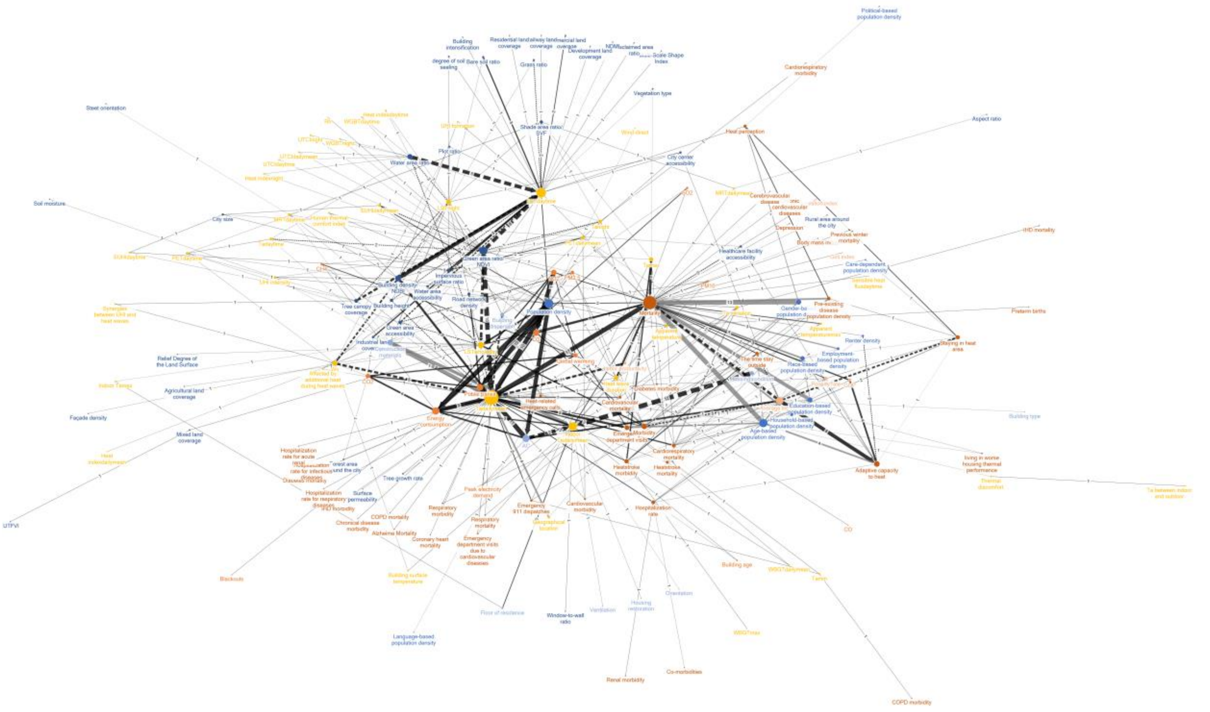

Figure 2. Quantitative causality map of urban heat vulnerability

2.2. Quantitative analysis of nodes and cause-effect links in the MCN

The number of times individual indicator nodes and their causal relationships have been verified is expressed in Figure 2. The size of each node indicates the number of times it has been validated by the study in the heat vulnerability evaluation, which can be interpreted as 'evidence.' Although it does not directly represent the strength of a causal relationship, generally speaking, a conclusion with a higher number of verifications means that its relationship is more prominent, making more researchers focus on it. However, it is challenging to quantify causality in a knowledge map where relationships are complex. In combination with 'evidence', the closeness centrality of individual nodes in the network was also counted to analyze the indicator node pattern further. The closeness centrality of a node represents its average distance (inverse distance) from all other nodes (Golbeck, 2013). It can efficiently disseminate information within a graph. In the MCN, nodes with the highest closeness score are closest to all other nodes, indicating their 'extent of association' to transfer causal information and their capacity to reflect how much they relate to heat vulnerability. A ranking of indicator nodes is provided in Figure 3. The node size represents the occurrence of indicators as 'evidence' while the Y axis shows the closeness centrality as 'association,' together displaying the node importance in the MCN.

Figure 3 shows the names and data of nodes with sizes equal to and more than 10 (distributed with a quartile of 75%). As another standard, the red line in the middle of the graph indicates the median value of closeness centrality. The exposure sector includes the most significant number of nodes with both substantial 'evidence' and 'association' because the discussion of temperature is the basis of any heat-related vulnerability assessment (Hammer et al., 2020; Kim et al., 2020; Liu et al., 2020). Another characteristic of the sector's indicators is the positive distribution of 'evidence' and 'association,' demographic and emissions show the same trend. However, for the most part, with substantial evidence, the association below the median, i.e., the causes, are more homogeneous. A similar situation exists for the human health sector, with only a few indicators such as mortality, morbidity, and others having an association above the median. Building stock and economy have the fewest indicators and the minor importance of any sectors but are not sufficiently different from the other sectors to neglect their impact on MCN.

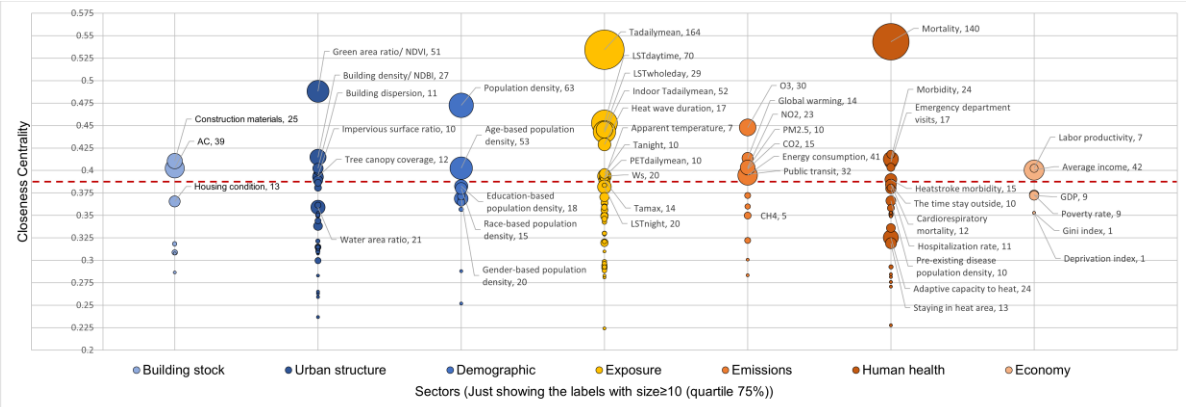

Figure 3. The distribution of node 'evidence' and 'association' in multi-sectors

To further validate the extent to which sectors represent causes or effects in the MCN, the concepts of in-degree and out-degree were introduced to analyze the distribution of indicators. The in-degree and out-degree of a vertex in a directed graph are the numbers of edges entering and leaving that vertex, respectively (Hansen et al., 2020). In this research, the difference between the two represents the causal attribute of the indicators. As shown in Figure 4, the sum of the in-degree and out-degree indicates an association similar to closeness centrality. As a result, the causal properties of building stock, demographic, and urban structure are all quite significant, with most indicators lying below the X axis. As a result, sectors of building stock, demographic, and urban structure are all fairly significant in terms of causal attributes, with the vast majority of indicators lying below the x-axis. As an intermediary sector, the distribution of exposure is quantitatively balanced in terms of causal components, but because LST is often used as one of the outcomes in heat vulnerability studies(Hulley et al., 2019; Meyers et al., 2020), its significance distribution is much higher than that of other indicators. The distributions of health and missions all show the outcome attributes. Among these, emergency consumption, public transit, etc. are the causes of emission gases in this sector. The most unusual sector is the economy, which is the effect sector in the MCN but has more cause attributes. However, the MCN still makes this decision for two reasons:

- The issue of labor productivity due to high temperatures has previously been little addressed in heat vulnerability studies.
- The economy directly determines the ability to implement mitigation strategies, which affects the regulation of heat vulnerability in turn.

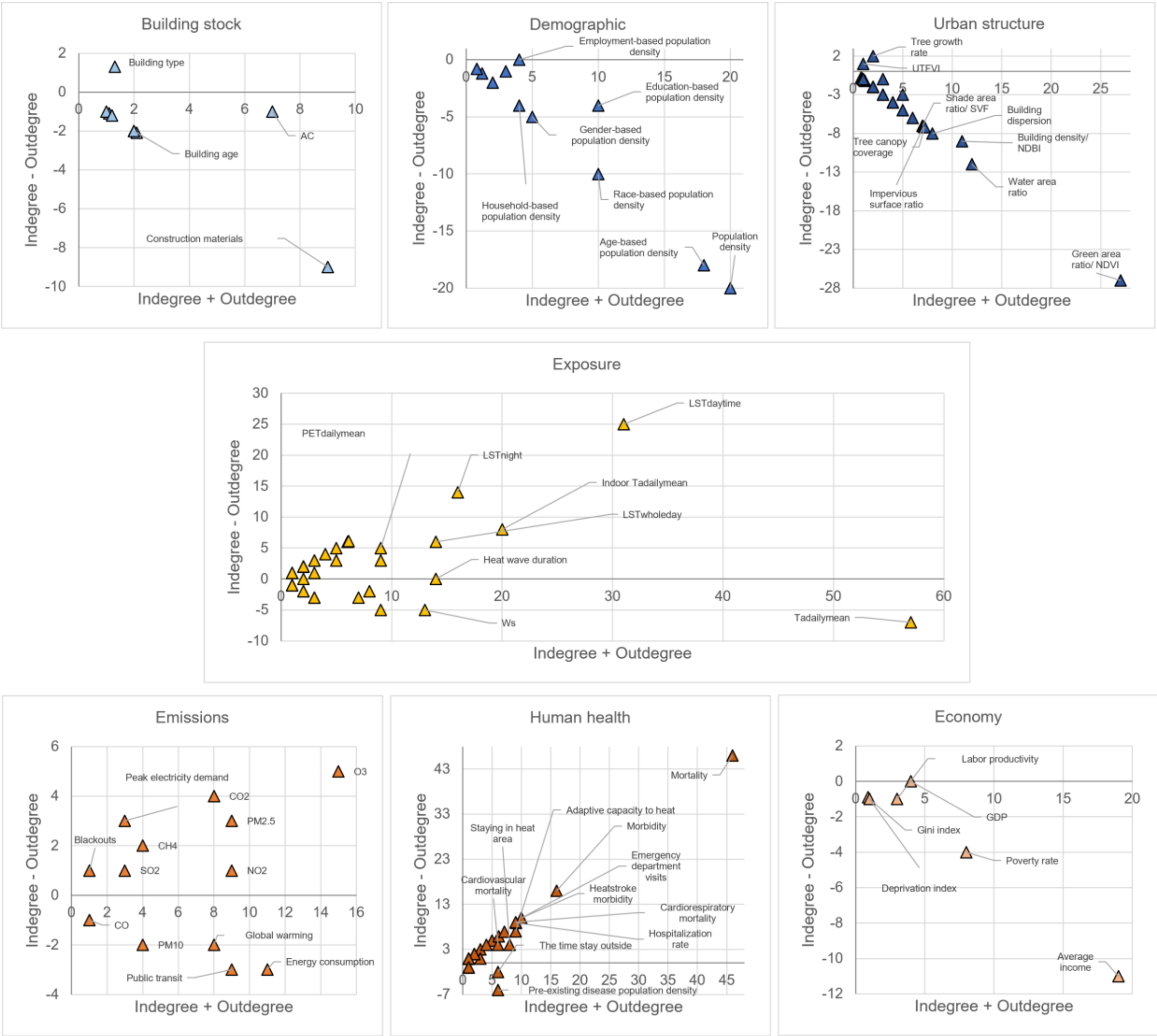

Figure 4 In-degree and out-degree distribution of indicators in multi-sectors

Is there a difference in the quantification of MCN when considering occurrences of each metric as weight and not considering only the number of relevant nodes? From Figure 5, it can be known that the tendencies under these two situations are similar. A moderate difference is that with the calculation of repeat nodes, the demographic and building stock sector will play more critical roles in the MCN. As discussed in Figure 3, the occurrence of each indicator is also necessary to be considered based on the method of scientific evidence summary. To avoid narrowing the demographic and building stock effect, the better way to continue the quantitative analysis is according to Figure 5 (a).

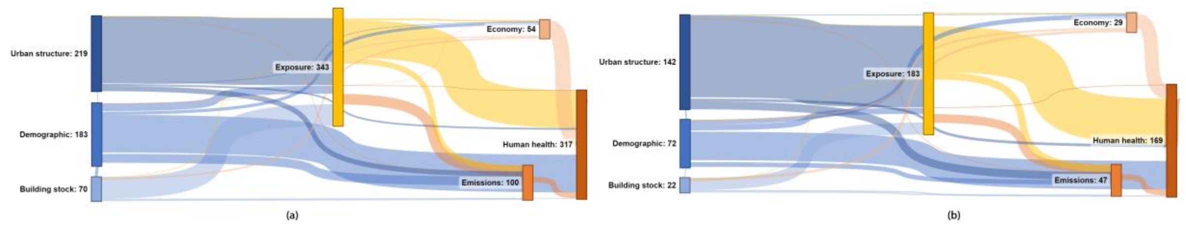

Figure 5 Comparison of the magnitude of cause-effect flow through multi-sectors between with calculation of repeat nodes and calculation without it

3. The causality from urban factors to their impacts

With the quantitative analysis in Section 2 as a basis, three levels of indicators can be extracted from the MCN according to different importance by the following steps. Figure 6 shows the causality from urban Factors to their impacts in the Sankey chart, representing the causal flows from causes to effects.

- Step 1 Extraction of indicators in main cause-effect flows: Focus only on causal flows with significant line widths.
- Step 2 According to Figure 3, inserting the indicators into each factor with priority levels based on quartiles: Level 1 (indicators in red) – occurrence/evidence ≥ Maximum value (100%) & closeness/association ≥ Q2 (50%), Level 2 (indicators in black) – occurrence/evidence ≥ Q3 (75%) + closeness quartile ≥ Q2 (50%), Level 3 (indicators in grey) – quartile ≥ 75% + closeness quartile < Q2 (50%). Since the previous review of the economy was conducted as a supplementary, considered a vital gap in the research field of heat vulnerability, most indicators of the economy are involved. The other indicators are not included in Figure 6. However, outliers based on Tukey's test (i.e., points above the Maximum value) are not considered to be outliers in a review-based study, as these figures are presented as important based on a large body of literature, not a single test. Therefore, when classifying the indicator level, level 1 is defined as those greater than the box plot's upper limit, which means these indicators have an overwhelming advantage over other indicators.
- Step 3 Validation of the significant indicators included in flow: Comparing the data from Figure 3 and Figure 4 again to ensure that no vital information flow is lost in the causal flow chart.

In Figure 6, the diagram above shows all positive causal flows, i.e., from causes to effects. Overall, each cause sector passes through the intermediary sector and into the effect sectors. In addition, the demographic sector also directly affects the economy and the sector of human health. The other two causes sectors also affect the sector of emissions. For the urban structure, most effects on the effect sectors are transmitted by exposure, as the urban LULC directly impacts the thermal environment (Berardi et al., 2020; Dong et al., 2020). Common indicators of LULC, such as building density, green area ratio, and building dispersion, also appear as Level 2 in the MCN. Unlike urban structure, most of the effects of demography are directly related to other effect sectors. For example, different population distributions can have different economic effects (Hatvani-Kovacs et al., 2016) and magnitudes of impact on human health (Kim et al., 2020; Lim and Skidmore, 2020). Also, high population density hurts energy and emissions (Arshad et al., 2020; Núñez-Peiró et al., 2021). Regardless of the direct effect on the sector, size-based population density and total population density are the most critical indicators in the demographic context. The difference in materials has a direct effect on indoor and outdoor temperatures. In contrast, all-cause sectors affect Ta and LST, while building stock also affects indoor temperature, focusing on the thermal exposure and thermal vulnerability of people indoors.

Turn to the causality from exposure to effect sectors. The most significant flow is the effect of high temperatures on human mortality and morbidity, followed by the direct negative impact of high temperatures on labor productivity (Herbel et al., 2018; Yi and Chan, 2017) and the load on emissions and energy consumption (Gronlund et al., 2020). It is also worth noting that the economy and emissions negatively impact human health through essential indicators such as income, GDP, and emission gases, further emphasizing that human health is the most important and ultimate effect sector in the whole MCN. It further emphasizes that human health is the most important and ultimate effect sector in the MCN.

In Figure 6, the graph below shows the feedback from effects to causes, which are more homogeneous and straightforward than the cause-effect linkages. Average income generates feedback on the application of AC to different populations (Karimi et al., 2018). In addition, missions contribute to increased urban extreme high temperatures in both the short and long term (Halder and Bandyopadhyay, 2021; Zhang et al., 2018) and are the most apparent feedbacks in the whole MCN that need to be considered in the future vulnerability assessment.

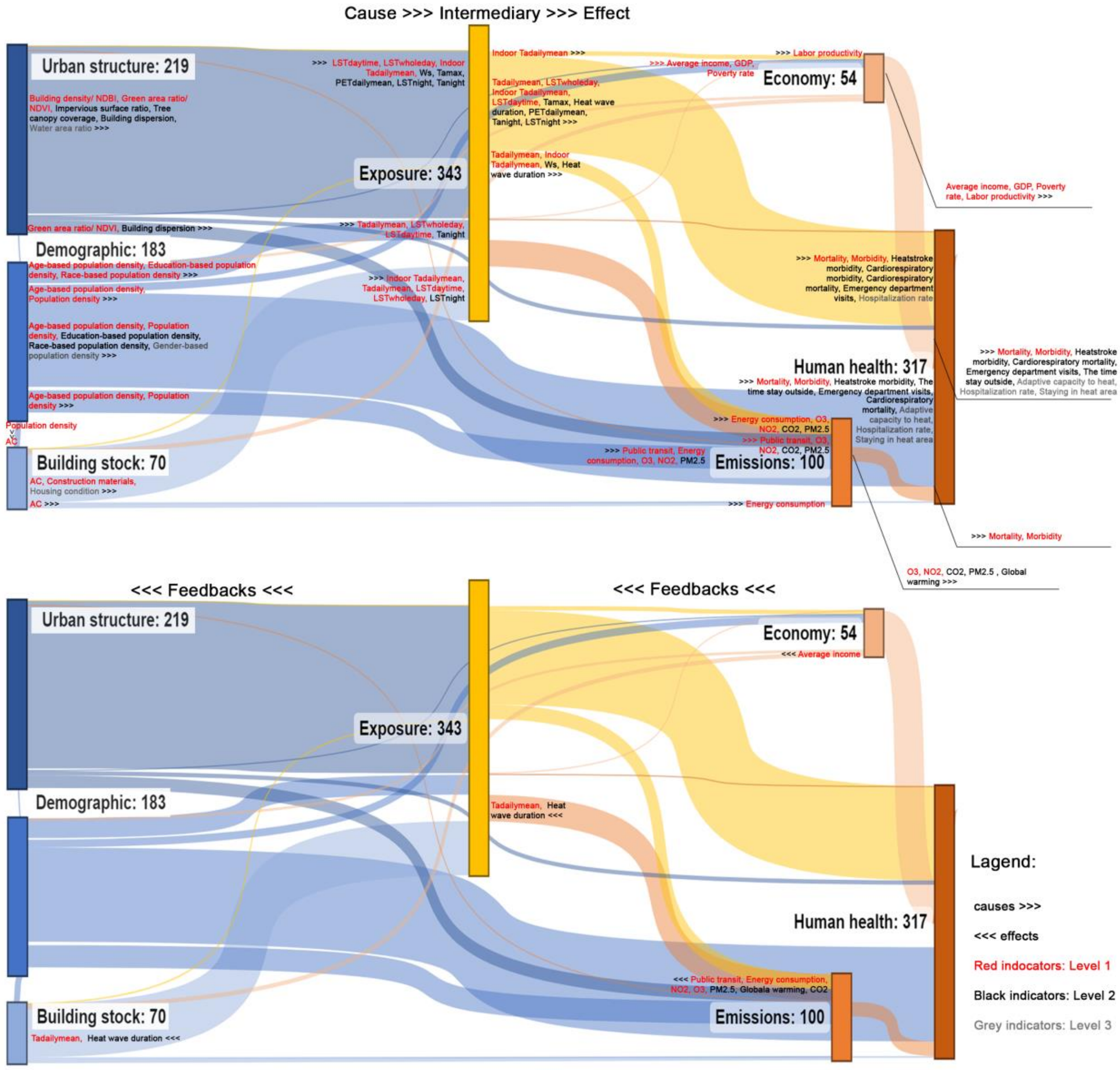

Figure 6 The causality from causal factors to effects through causal flows in the Sankey chart

The indicators within each sector were further analyzed, and the results are shown in Table 1. NV is the number of indicators in each sector. RER represents the cycle in this sector, only in the exposure, specifically the vicious cycle of increased outdoor temperature, which leads to increased indoor temperature and AC use, further leading to the increased outdoor temperature. MVCC and MECC represent the degree of interconnectedness of the indicators within the sector. The larger the number, the more interconnections there will be and the stronger the covariance of the indicators in future evaluations, so it is not necessary to present all of them. SVCC refers to the number of indicators only causally linked to other sectors, with emissions showing a solid autocorrelation. The distance, the more cause-effect hierarchies within the sector. The most hierarchical sectors were Human health, exposure, and missions that order.

Table 1 Indicator distribution analysis within individual sectors

Sectors	Nv	Te	RER	SVCC	MVCC	MECC	MGD	AGD
Building stock	9	0	/	9	1	0	/	/
Demographic	11	3	0	7	4	3	3	1.250
Urban structure	41	2	0	37	2	1	1	0.500
Exposure	43	18	0.111	25	14	16	5	2.245
Emissions	13	15	0	3	10	15	4	1.700
Human health	41	21	0	22	19	21	6	2.831
Economy	6	0	/	6	1	0	/	/

Note:
NV-Number of vertices
TE-Total Edges
RER- Reciprocated Edge Ratio
SVCC-Single Vertex Connected Components
MVCC-Maximum Vertices in a Connected Component
MECC-Maximum Edges in a Connected Component
MGD-Maximum Geodesic Distance (Diameter)
AGD-Average Geodesic Distance

From a macro qualitative perspective, the new definition of urban heat vulnerability is 'the propensity and extent to which urban structures, buildings, and population groups are negatively affected by severe warmth, resulting in changes in emissions, human health, and the economy.' For each effect sector, the vulnerability indicator lateral focus has apparent differences. For the economy and human health, the impact from demographic should be stressed, while for the emissions, the impact from urban elements should be treated as much more critical.

4. Conclusions

The quantitative analysis of the MCN (Multi-sector causal network) of urban heat vulnerability shows that different sectors have different magnitudes of causal flows and further validates the reasonableness of the cause. The results of the quantitative analysis show that different sectors have different magnitudes of causal flows. The level classification of the indicators in the seven sectors can provide an essential reference for the priority selection of future vulnerability assessment indicators. The redefinition of urban heat vulnerability in this study specifies and extends the scope of the current research field, making it possible to make integrated links with sectors other than urban design and population distribution. At the same time, the results of this study suggest that future decision-makers and stakeholders should weigh the pros and cons of urban heat vulnerability as more than a fuzzy concept when making decisions about the urban thermal environment.

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