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Review

Applications of Local Climate Zone Classification Scheme to Improve Urban Sustainability: A Bibliometric Review

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Abstract: Many of the sustainable urban development issues, such as human heath, energy consumption, carbon emission, are related to the climate of cities. As a result, research insights gained in urban climate study can be applied to improve urban sustainability. Although the Local Climate Zones (LCZ) scheme was originally proposed to provide a standardized classification of landscapes to study urban air temperature, its use was not limited to the study of urban heat islands. This study explores the applications of LCZ scheme in various research domains by conducting a bibliometric analysis in CiteSpace on over 800 articles that cites the original article of LCZ. These articles cover a wide range of research categories including meteorology, atmospheric science, environmental science, remote sensing, building technology, civil engineering, ecology, urban studies, etc. The LCZ scheme facilitates urban climate data collection by refining monitoring network, providing reasonable modelling input, and improving database documentation. In addition to the study of urban heat islands, the LCZ scheme was applied in studies of urban thermal comfort, human health, building energy consumption, and carbon emission. The diffusion of the LCZ scheme to other research domains offers an example that the development of urban climate research advances sustainable urban development. This review provides insights of multidisciplinary studies related to urban climate for policy-makers, urban specialists, architects, ecologists, and others.

Keywords: Local Climate Zone (LCZ); urban climate; urban heat island; thermal comfort; carbon emission; sustainable urban development; building energy consumption

1. Introduction

A total of 56% of the world population lives in cities in 2020 [1], as a result of rapid urbanization. Urbanization greatly changes the form, fabric, structure, and metabolism of a landscape, and thus alters the local climate of that area. Urban heat island (UHI), which refers to the higher ambient temperature in a city compared to its rural parts [2], has deteriorated urban sustainability. For example, higher ambient temperature worsens human thermal comfort in the summer [3], and may even led to increased mortality [4] due to increased heat stress. In addition, UHI advances the start of season for urban plants [5], and contributes to greater air conditioning energy consumption [6] for buildings.

Due to the significant impact of UHI on urban sustainability, researchers have made large effort in understanding UHI. However, the documentation of UHI intensity in literature may be inconsistent and inaccurate due to vague definition of urban and rural areas. What is described as urban in one city or region differs from that of another. In order to provide an objective protocol for measuring the strength of urban heat island, and to facilitate controlled inter and intra comparisons of UHI results, Stewart and Oke [7] proposed the Local Climate Zones (LCZ) classification system. The LCZ scheme clusters landscapes into different "local climate zones" based on their approximate ability to modify local surface climates due to their typical fabric, land cover, structure, and metabolism.

The scheme has attracted huge research attention. Eight years after the proposal of the LCZ scheme in 2012, the original article has been cited more than 800 times (as of July 2020, Web of Science database). While the original purpose of the LCZ scheme is to simplify and standardize urban temperature observations, its application has been diffused to many other research areas that are related to sustainable urban development, such as urban planning [8], building energy consumption [9–13], human perception of outdoor spaces [14], etc.

The diffusion of the LCZ classification system to related domains has demonstrated the rich connotation and multidisciplinary nature of urban climate research. To provide useful information and to identify research opportunities and new frontiers to the urban climate and related research communities, this study reviews the applications of the LCZ scheme in different research topics with aid from a bibliometric tool. The contents summarized in this paper are by no means exhaustive, but an indication of the trend of using LCZ in urban research.

2. Methods

2.1. Concept, Data, and Tool

Stewart and Oke [7] formally proposed the LCZ Scheme in their article "Local Climate Zones for urban temperature studies" in *Bulletin of American Meteorological Society* in 2012. According to Stewart and Oke [7], urban or rural spaces were classified into one of the 17 local climate zones based on the fabric (thermal admittance, surface albedo), land cover (plan fraction occupied by buildings, vegetation, and impervious ground), structure (sky view factor, aspect ratio, roughness element height), and metabolism (anthropogenic heat output) of that space. 10 out of the 17 zones are for "built types" with various spatial arrangements and heights, and the remaining 7 types are natural landscapes without artificial structures. Spaces clustered into the same LCZ have similar ability to modify local surface climate. From the definition, it can be seen that LCZ was originally created for the purposes of urban climate studies.

The original LCZ manuscript [7] has been cited by a large number of references covered by various disciplines. Our analysis has used all the articles and reviews in English that cite Stewart and Oke [7] in the Web of Science Core Collection dataset for the bibliometric analysis. The retrieval of data was performed on 26 July 2020, and 884 bibliographic items with their titles, keywords, abstracts, cited references, research categories, and authors and their institutions were exported for further analysis in the CiteSpace 5.7.R1 [15], which is a program for quantifying and visualizing relationships among scientific literatures. CiteSpace provides a visual gateway to the literature of scholarly publications. It shows on the collective behavior of peer scholars and experts in terms of which articles they cite, how often they cited, and contexts in which they cite.

2.2. Performed Analyses

The downloaded dataset was firstly descriptively analyzed by studying its temporal distribution, contributing countries, institutions, journals, and authors. Then, as the main objective of this study, various research topics that used LCZ were identified by CiteSpace by generating and clustering the co-citation network. Selected publications from these research domains were further reviewed. Finally, CiteSpace was used to reveal the network of different disciplines that adopted the LCZ scheme.

3. Results

3.1. Descriptive Analysis

The first part of the Results section shows the basic statistics of the LCZ-related publications. Figure 1 shows the temporal distribution of the number of publications that cite the original article [7] from 2013 to 2020 July. The researches related to LCZ dramatically increased from 19 in 2013 to 220 in 2019, highlighting the growing of global interest on the LCZ scheme.

Table 1 lists the main contributing journals. These journals cover a wide range of subjects, such as meteorology, environmental science, building science, urban science, energy, and remote sensing technology. *Urban Climate* published the most items (97), which is not surprising, since LCZ is originally derived from urban climate research. *Science of the Total Environment*, *Building and Environment*, *Sustainable Cities and Society*, and *Remote Sensing* ranked from 2 to 4 with 48, 39, 35, and 33 contributing records, respectively.

Table 1. A ranking of contributing journals.

#	Journal	# of Records
1	Urban Climate	97
2	Science of The Total Environment	48
3	Building and Environment	39
4	Sustainable Cities and Society	35
5	Remote Sensing	33
6	International Journal of Climatology	27
7	Landscape and Urban Planning	25
8	Sustainability	22
9	Theoretical and Applied Climatology	22
10	Journal of Applied Meteorology and Climatology	17
11	Atmosphere	16
12	Energy and Buildings	14
13	Remote Sensing of Environment	13
14	Climate	12
15	Environmental Research Letters	12
16	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	12
17	Urban Forestry and Urban Greening	12
18	Atmospheric Environment	11
19	Journal of Geophysical Research Atmospheres	11
20	ISPRS International Journal of Geo Information	10
21	International Journal of Biometeorology	9

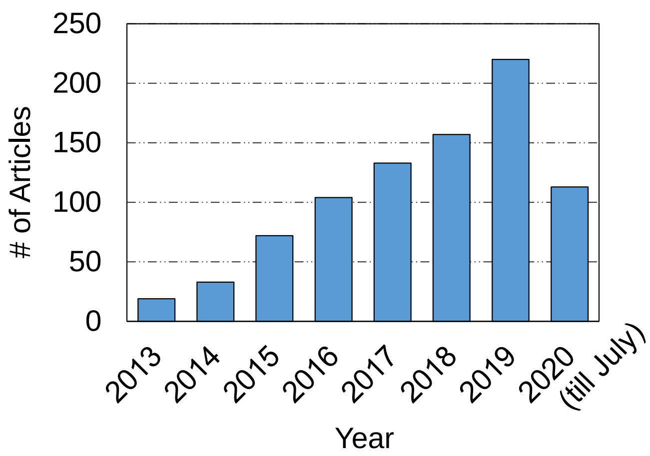

Figure 1. Annual distribution of the bibliographic dataset.

Table 2 shows the major contributing countries in terms of publication. Four countries have more than 100 LCZ-related publications, with China taking the first place with 276 records, followed by the USA with 199 records. Germany and England have contributed 145 and 103 items, respectively.

Table 2. A list of contributing countries and contributed number of records.

#	Countries	# of Records
1	China	276
2	USA	199
3	Germany	145
4	England	103
5	Canada	62
6	Australia	57
7	Italy	47
8	Netherlands	42
9	Austria	36
10	Belgium	36
11	France	36
12	Japan	32
13	Singapore	30
14	India	26
15	South Korea	26
16	Spain	24
17	Switzerland	23
18	Ireland	21
19	Brazil	19
20	Czech Republic	19
21	Sweden	17
22	Hungary	16
23	Greece	15

The top contributing institutions are presented in Table 3. Arizona State University ranked first (112 records), followed by Chinese Academy of Sciences (87 records). Among the top 19 institutions, China and Germany have four institutions, while America has three.

Table 3. A ranking of contributing institutions by number of records.

#	Institutions	# of Records
1	Arizona State University	112
2	Chinese Academy of Sciences	87
3	University of Reading	52
4	University of Hamburg	50
5	University of Hong Kong	37
6	Helmholtz Association	33
7	University of New South Wales Sydney	28
8	Chinese University of Hong Kong	25
9	German Aerospace Centre	22
10	Ghent University	22
11	University of California System	22
12	Centre National De La Recherche Scientifique	21
13	Wageningen University Research	21
14	KU Leuven	19
15	National University of Singapore	19
16	China Meteorological Administration	18
17	Humboldt University of Berlin	17
18	University College Dublin	17
19	Massachusetts Institute of Technology	16

Table 4 shows the top 10 most productive authors across all countries. Bechtel B ranked first with 35 items, followed by Grimmond CSB, who published 33 records.

Table 4. Top 10 authors ranked by number of contributions.

#	Authors	# of Records
1	Bechtel B	35
2	Grimmond CSB	33
3	Ren C	24
4	Demuzere M	21
5	Mills G	16
6	Masson V	15
7	Xu Y	15
8	Martilli A	14
9	Middel A	14
10	See L	14

3.2. Research Topics

In order to identify the research topics for publications related to LCZ, a document co-citation network was generated. Co-citation is defined as the frequency with which two documents are cited together by other documents. A co-citation network provides a tool for monitoring scientific development [16]. After generating the co-citation network, the publications with close relationships were grouped into 12 clusters, as shown in Figure 2. Label was created automatically for each cluster in CiteSpace by summarizing the main theme of publications in a cluster. Ranked by the size (number of publications) of the clusters, the main labels are surface urban heat island (SUHI), outdoor thermal comfort, local climate zones, Surface Urban Energy and Water Balance Scheme (SUEWS), crowdsourcing, human health, risk assessment, carbon dioxide, building performance simulation, knowledge base, heat wave, and urban databases. These labels demonstrate the wide range of topics covered in the LCZ-related researches.

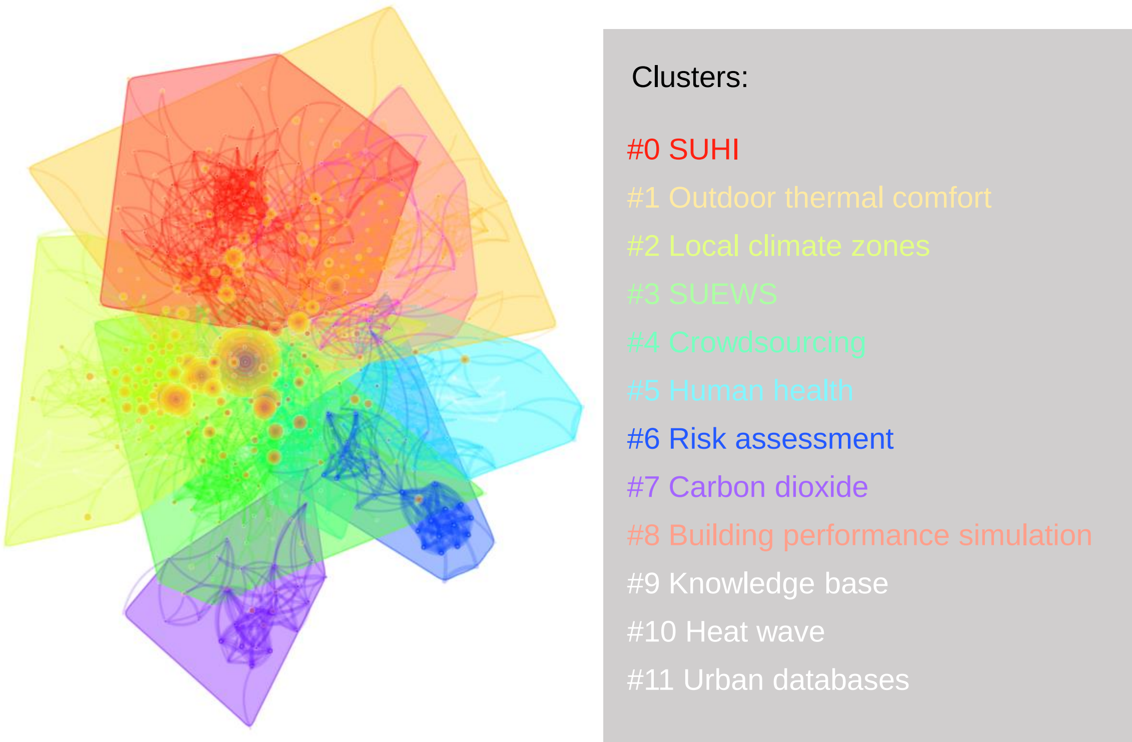

Figure 2. The co-citation network and cluster.

Table 5 further provides the detailed size information and the top five labels identified in CiteSpace for each cluster. The research topics were summarized from the identified terms. For example, the largest cluster (#0) had a lot of terms indicating techniques, indicators, and tools associated with urban heat island, while the terms in second largest cluster (#1) were about index, research approach, and modelling tool of outdoor thermal comfort. Thus, urban heat island and outdoor thermal comfort were chosen as research topics identified from cluster #0 and cluster #1, respectively. By using a similar approach, cluster #2 was named as local climate zone, cluster #3 as model, #4 as monitoring, #5, #6, and #10 as human health, #7 as carbon emission, #8 as building energy, #9 and #11 as database.

Table 5. Cluster description and the top five labels within each cluster.

Cluster ID	Size	Top 5 Labels
0	109	surface urban heat island, land surface temperature, MODIS (Moderate Resolution Imaging Spectroradiometer), thermal remote sensing, urban heat island effect
1	102	outdoor thermal comfort, Envi-met, thermal comfort, PET (Physiologically Equivalent Temperature), field survey
2	101	local climate zones, remote sensing, Sentinel-2, urban areas, convolutional neural network
3	78	SUEWS (Surface Urban Energy and Water Balance Scheme), energy balance, WRF (Weather Research and Forecasting Model), land surface model, regional climate modeling
4	61	crowdsourcing, citizen weather station, cyber-infrastructure, wireless sensor networks, crowdsourcing air temperature
5	45	human health, NDVI (normalized difference vegetation index), thermal behavior, synoptic weather type, cool pavements
6	40	risk analysis, mortality, Germany, intra-urban air temperature, Envi-met modeling
7	29	carbon dioxide, eddy covariance, source area, urban environment, emissions inventory
8	29	building performance simulation, sea breeze, density, urban weather generator, urban building energy performance
9	6	knowledge base, personal weather station, relative land surface temperature, human health, building
10	5	heat wave, thermal comfort, air temperature, local climate zones, urban climate
11	5	urban databases, CO_2 fluxes, urban climate maps, urban canopy layer model, MApUCE

As shown in Figure 3, the nine topics were further organized into three levels, with the first level being the researches of the LCZ scheme itself. The second level includes topics of database, monitoring, and modeling, which are related to LCZ data and adopting LCZ in monitoring and modeling to obtain urban climate data. Level 3 uses the climate data to address specific urban issues such as UHI, thermal comfort, health, building energy, and carbon emission. The following provides a topic by topic review of the research areas related to LCZ. The review is not trying to be inclusive, but to provide examples of researches areas around LCZ and application of such a concept from urban climate research to related subjects.

3.2.1. Level 1: Local Climate Zones (LCZ)

A large portion of publications is relate to the study of the LCZ scheme itself, such as the evaluation, application, and improvement of the scheme. Stewart et al. [17] have justified the division of urban and rural landscapes into LCZs by demonstrating significant temperature difference among LCZs from site observations and atmosphere-surface model simulations. The authors suggested further evaluation of LCZ by advanced numerical models and more UHI observations.

Generating LCZ maps for cities is an important step to facilitate urban studies, and some studies were mainly about the generations of LCZ classification maps for various cities, such as in Hong Kong [18], Xi'an [19], and three metropolitan areas of Texas, U.S. [20]. According to Zheng et al. [18], there are mainly three methods of LCZ classification methods: manual sampling, remote sensing, and geographical information system (GIS). The remote sensing method has been adopted by the World Urban Database and Access Portal Tools (WUDAPT). However, Ren et al. [21] has found the WUDAPT method to be inaccurate for creating LCZ maps for Chinese cities due to the lack of building height data, and a feasible refinement method was proposed by the authors.

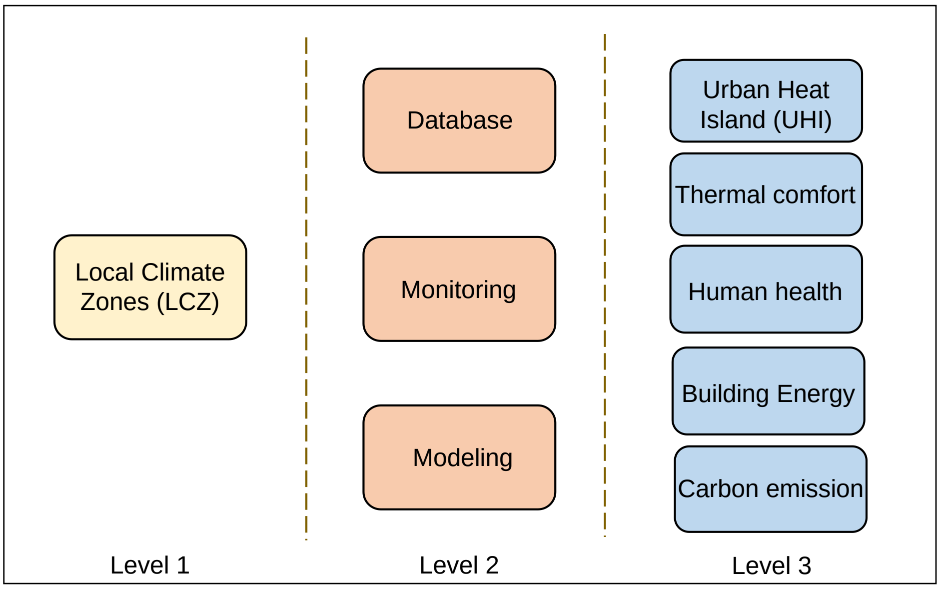

Figure 3. Identified research topics related to Local Climate Zones (LCZ).

3.2.2. Level 2: Database

Consistent, detailed, and easily available urban data is essential to promote the development of urban climate and related sciences. The WUDAPT project was launched to provide useful information that describes aspects of the form and function of cities at a detailed spatial resolution [22]. The WUDAPT initiative is a global, bottom up, self-organized effort to fill the data gaps needed to solve the global challenges of sustainable cities and communities, and as a guide to facilitate climate-based actions [23]. The urban information in WUDAPT is conveyed through the form of LCZs at different levels of details, and the remote sensing data is used to create LCZs for urban and natural landscapes of cities in WUDAPT [24].

3.2.3. Level 2: Monitoring

Urban meteorological monitoring is important because it is an essential mean to obtain climatic data for further assessment urban heat island, outdoor thermal comfort, health, building energy consumption, etc. With environmental sensors becoming more compact, inexpensive, and reliable, it is possible to deploy a dense urban meteorological monitoring network for a better understanding of the heterogeneous urban environments [25]. Crowdsourcing, the utilization of residents or public sensors for the obtain of data, is an alternative of urban monitoring. By using smartphone battery temperature, UHI effect has been found in some of the LCZs in São Paulo, Brazil [26]. The LCZ scheme is also useful to ensure that certain representative areas are monitored when designing the urban monitoring network [27].

3.2.4. Level 2: Modeling

As stated in the original article [7], one of the applications of LCZ is to provide urban canopy parameters for numerical climate models to predict temperature, wind, precipitation, etc. Alexander et al. [28] examined the validity of using LCZ data to run the Surface Urban Energy and Water Balance model (SUEWS). They found the simulation using the LCZ scheme and meteorological data from a station outside the urban area showed good agreement with the observation records across multiple seasons, thus validating the capability of LCZs for the parameterization of SUEWS.

3.2.5. Level 3: Urban Heat Islands (UHI)

Since the original purpose of LCZ scheme is to provide a standardized classification of site in urban heat islands (UHI) studies, it is not surprising that UHI is the largest cluster in Table 5. UHI includes surface temperature UHI and air temperature UHI [29]. Surface UHI is the temperature difference of urban and rural grounds and can be measured by remote sensing observations. During the UHI study, researchers classified the investigated sites into specific LCZs and reported the measured or predicted air temperature, surface temperature, and related parameters. For example, Middel et al. [30] simulated the mid-afternoon microclimate of five LCZs in Phoenix, Arizona, USA, and concluded compact scenarios were favorable for daytime cooling. Van Hove et al. [31] used data from a monitoring network in Rotterdam agglomeration that covered a range of LCZs for the analysis of temporal and spatial variability of UHI. UHI influences human thermal comfort, health, building energy consumption, and carbon emission. As a result, the LCZ scheme can be further applied in the above topics.

3.2.6. Level 3: Outdoor Thermal Comfort

Human thermal comfort in outdoor spaces is significantly related to the microclimate condition, such as air temperature, radiation, wind, etc. [32–34]. These parameters in urban spaces are spatially variable due to the modification of surface energy and radiation balance in different local climate zones. As a result, occupants have different thermal comfort perceptions in various LCZ zones, as evidenced by Lau et al. [35] in Hong Kong, China, Liu et al. [36] in Shenzhen, China, and Das et al. [37] in Eastern India. The LCZ scheme helps thermal comfort researchers to document the studied sites in a standardized way [38,39]. The scheme also offers a tool for researchers to select suitable sites to conduct thermal comfort survey [14].

3.2.7. Level 3: Human Health

Urban climate is a driver of many health issues, such as heat-stress related mortality, vector-borne disease, and air quality problems. There is a well-established connection between extreme heat and summer excess mortality [4]. Since LCZs contain important urban morphological characteristics that is related to spatial air temperature regimes, Verdonck et al. [40] examined the potential of using LCZ maps as heat stress assessment tool in three cities in Belgium: Antwerp, Brussels, and Ghent. The effect of thermal stress on human health can also be assessed by using indices such as Physiologically Equivalent Temperature (PET) [41] or the Universal Thermal Climate Index (UTCI) [42]. In addition to heat stress, air quality and its impact on human health in urban spaces is a pressing issue in city. The distributions of air pollution concentration are controlled by the urban flow field, which is strongly impacted by urban geometry [43]. Vector-borne disease is another health problem related to urban climate, since there is a link between air temperature and the vector behaviors. In Sub-Saharan Africa, to study intra-urban malaria risk, Brousse et al. [44] combined LCZs and very high resolution satellite imagery for the parameterization of a simple urban canopy model, and derived a Temperature Suitability Index (TSI) map for the evaluation of vector-borne malaria disease.

3.2.8. Level 3: Building Energy

Since the building and its heating, ventilation, and air-conditioning (HVAC) system directly exchange heat with the environment adjacent to the building, the cooling and heating energy of that building is externally determined by its surrounding microclimate. Building energy simulation provides useful insights for the design, construction, operation, and control of buildings, but traditional simulation usually uses the meteorological data collected from rural or suburban stations as background climate input, and thus fails to account for the altered climatic condition by urban elements. Yang et al. [9] simulated and compared the energy performance of buildings located in different local climate zones (LCZ) and found a difference of up to around 20% in cooling and heating loads. The result indicates the importance of using site-specific data for a more accurate evaluation of energy performance of buildings in urban contexts.

3.2.9. Level 3: Carbon Emission

Concentrated anthropogenic activities in urban areas has led to intense carbon emission. Since the morphological and functional structure of city spaces is closely associated with the carbon emissions, it may be practical to adopt the LCZ scheme to study building carbon emission in cities. Wu et al. [45] preliminarily investigated the building carbon emission of different LCZs in Shanghai, and demonstrated that LCZ 1 (compact high rise) emitted more carbon than other LCZs. LCZs also provide a method to categorize the feature of investigated sites in carbon modeling research. For example, Jarvi et al. [46] validated their CO_2 exchange model against the data collected from two sites, which were classified as LCZ 2 and LCZ 6.

3.3. Research Subjects

In order to visualize the relationships among subjects that adopts the LCZ scheme, CiteSpace was used the generate the network of co-occurring research categories. The network was shown in Figure 4. The thickness of the links between subjects denotes the strength of relationships, and the size of the node represents usage frequency of the subjects. We found that environmental science & ecology, meteorology and atmospheric sciences, remote sensing, construction and building technology, engineering are major subjects with large nodes. Minor subjects include urban studies, green and sustainable science and technology, ecology, geography, public administration, forestry, etc.

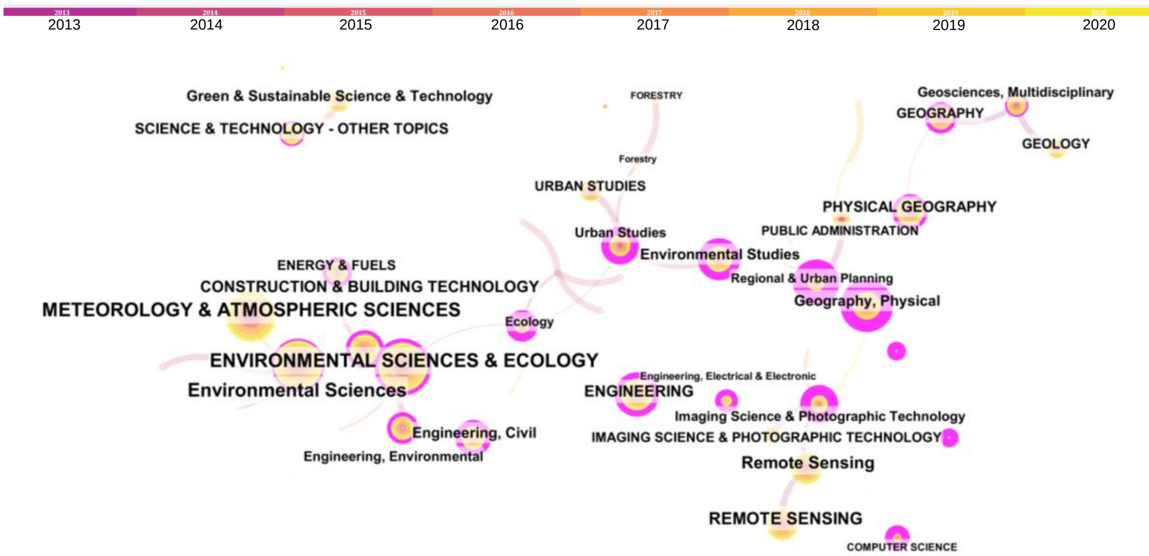

Figure 4. Network of co-occurring research categories.

The rings around a node shows the temporal evolution of the subject. The inner rings show the older usage while the outer rings are indications of newer usage. It can be seen that the studies related to environmental sciences, meteorology and atmospheric science, and remote sensing are older than the studies in urban planning, engineering and geography, etc. This phenomenon indicates that LCZ was originally developed and used in the meteorological, environmental sciences and remote sensing areas, but later, its uses were diffused to the fields of urban studies, engineering, construction and building technology. Table 6 lists the top 10 research categories and their percentage.

Table 6. Top 10 research categories and their percentages.

#	Category	%
1	Environmental sciences & ecology	32
2	Meteorology & atmospheric sciences	15
3	Remote sensing	6
4	Engineering	6
5	Construction & building technology	5
6	Science & technology - other topics	4
7	Geography, physical	3
8	Engineering, civil	3
9	Green & sustainable science & technology	3
10	Energy & fuels	3

4. Discussion

From the above review, it can be found that the LCZ scheme advanced the urban studies in two ways. Firstly, some urban studies such as thermal comfort, health, and building energy highly depend on the urban climate data. Urban climate data collection was improved with LCZs by aiding the monitoring, modeling, and database creation. Second, the LCZ scheme provided a guideline for related studies to select suitable spaces to conduct investigations, and the scheme also offers a standardized way to document studied areas.

The LCZ scheme was also applied in topics beyond the research areas detected in our bibliometric analysis. For example, urban ventilation is strongly impacted by architectural patterns and may be studied with the help of LCZs. Zhao et al. [47] offered evidences that the LCZ classification scheme could effectively indicate local-scale urban ventilation performance. Yang et al. [48] adopted LCZs in the study of urban ventilation in Shanghai, while Zhou et al. [49] found that LCZs could be employed to understand the cooling potential of sea-land breeze in Sendai, Japan. Actually, LCZs can be applied in any research fields influenced by the urban heat island; to name a few, urban plant and urban air pollution studies. For example, the start of season (SOS) for plants was found to be associated with UHI [5], and LCZs can be useful to detail the spatial variation of plant SOS. Lower urban aerosol pollution island (UAPI) is detected with increased UHI [50,51], and LCZs can also be used to provide more details.

With the expansion of applications in urban climate research, it is necessary to always be careful when applying LCZs to other domains. Bartesaghi et al. [52] pointed out that LCZs are not well-suited for the microclimatic analysis of green infrastructure (GI), since the LCZ scheme provides limited information on the dynamic interactions between vegetated and built environments. As a response, Bartesaghi et al. [53] developed green infrastructure typology (GIT) framework.

5. Conclusions

The Local Climate Zone (LCZ) scheme was originally proposed to provide a standard method for consistent documentation of urban and natural landscapes for urban heat island studies. However, the LCZ scheme has been used in many subjects related to urban sustainability. It is interesting to know the diffusion of knowledge in urban climate research to other disciplines. This study investigated the diffusion of the LCZ application to other research domains by applying a bibliometric method. The analysis of a bibliometric dataset has identified nine research topics, includes LCZ itself, creating urban database, urban climate monitoring, urban climate modeling, urban heat island, outdoor thermal comfort, health, building energy consumption, and carbon emission. The LCZ scheme has advanced the related research topics such as human thermal comfort, health, building energy consumption by providing more reliable and detailed urban climate data and a consistent classification method to document the studied spaces. An analysis of research categories shows that the LCZ scheme and classification method was initially developed and frequently used in subjects like meteorological science, environmental science, and remote sensing. Later, its uses were diffused to applied fields such as urban and regional planning, building and construction technology, engineering, and ecology, etc.

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