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Evaluation and Utilization of Thermal Environment Associated with Policy: A Case Study of Daegu Metropolitan City in South Korea

Jeong-Hee Eum [1,*], Kwon Kim [2], Eung-Ho Jung [3] and Paikho Rho [3]

1 Department of Landscape Architecture, Keimyung University, 1095 Dalgubeol-daero, Daegu 42601, Korea
2 Department of Architecture, Graduate School, Keimyung University, 1095 Dalgubeol-daero, Daegu 42601, Korea; kimkwon258@gmail.com
3 Department of Environmental Planning, Keimyung University, 1095 Dalgubeol-daero, Daegu 42601, Korea; turep21@kmu.ac.kr (E.-H.J.); wildlife@kmu.ac.kr (P.R.)
* Correspondence: eumjh99@kmu.ac.kr; Tel.: +82-53-580-5646

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Abstract: This study aimed to propose a way to utilize vulnerability assessment effectively in policy-making by conducting policy-related assessment of the thermal environment. For this purpose, a variety of indices concerning thermal vulnerability assessment were reviewed, and finally, 15 indices were selected. In addition, adaptation policies for climate change applied to Korean cities were synthesized and examined to establish policies for improving thermal environments which correspond to 15 indices. Finally, a framework consisting of five areas (improvement of the atmospheric environment, expansion of eco-friendly buildings, management of the surface, cool spot creation and revitalization of communities), 15 indices and 25 policies was proposed. As a result, 15 vulnerability maps based on the standardized indices and a comprehensive map with four classes were established for Daegu Metropolitan City in South Korea. Based on the maps, Guji-myeon and Ansim-1-dong were found to be the most vulnerable areas. Hence, the causes of the thermal environment vulnerability and the policies for improving urban thermal environment were analyzed in these two areas using the proposed framework. Guji-myeon was necessary to more actively implement policies regarding the improvement of the atmospheric environment, management of the surface, and revitalization of communities. To improve the thermal environment of Ansim-1-dong, active policy implementation was required in all five areas. The results of this study are expected to contribute to the effective establishment of thermal environment policies by policy-makers.

Keywords: thermal environment; vulnerability assessment; policy-linked index; climate change adaptation

1. Introduction

Various environmental problems, such as deterioration of the thermal environment, flood occurrence, and air pollution have intensified in urban areas owing to the effects of global warming resulting from climate change. Solar radiation is the main cause of the increase in air temperature. Heat transfer from the surface to the atmosphere has increased because of the change in thermal properties of surface materials [1–3]. Exhaust airflow and radiant heat have increased from increased air conditioner use and exhaust heat from factories and automobiles, thereby raising the temperatures of city atmospheres. In addition, the total area that reflects and absorbs sunlight has expanded owing to the high heat capacity of building materials, such as concrete. Higher heat absorption of buildings and lower radiation cooling have led to high building temperatures, which then increases air conditioning usage and artificial exhaust airflow [4–9]. As the pavement surface area has expanded because of artificial materials such as asphalt, the green belt and water surface areas have shrunk. Consequently, evapotranspiration from the surface has decreased, causing the surface and atmospheric temperatures to rise [10–12]. Therefore, it is necessary to locate areas vulnerable to thermal environment intensification due to climate change, identify the causes of the vulnerability, and establish policies to improve the situation.

The Intergovernmental Panel on Climate Change (IPCC) defined vulnerability as a function of the character, magnitude, and rate of climate change and variation to which a system is exposed as well as its sensitivity and adaptive capacity [13]. Hence, vulnerability to the thermal environment should be evaluated by considering exposure, sensitivity and adaptive capacity. Globally, studies have been conducted to assess climate change vulnerability according to this definition for using the results in policy establishment and institutionalization [14]. However, the lack of information on how to reduce the vulnerability based on this assessment limits its use by policy-decision makers [15].

Daegu Metropolitan city is one of most vulnerable cities to excessive heat events in South Korea. Hence, studies on effective policies as well as analysis and assessment methods of the urban thermal environment have been conducted. These studies have included an evaluation method of the spatial characteristics for creating wind ventilation paths in Daegu region [16], the expansion and operation of the policy 'clean-road system' for spraying water on roads [17] and an analysis of the thermal environment based on satellite images and Automatic Weather System (AWS) data [18]. In addition to efforts by vulnerable local governments to reduce excessive heat events and to manage the impacts of climate change, the Korean government has established the 'comprehensive basic plan for climate change response' and the 'comprehensive national adaptation plan for climate change' to respond and adapt to climate change at the legal level. In particular, since 2010, the government has made legal efforts by enacting the 'Low-carbon Green Growth Act' which obliges local governments to establish a detailed implementation plan for climate change adaptation measures. To establish this plan, local governments classify climate change vulnerability into seven categories, including health, disasters, agriculture, and forests. In addition, the Ministry of Environment and the Korea Adaptation Center for Climate Change operate the 'vulnerability assessment tool to build climate change adaptation plan (VESTAP)' which contains basic data on climate change vulnerability and vulnerability assessment function to indirectly help local governments establish a detailed adaptation plan for climate change [19]. However, as the specific improvement policy has not been presented according to the results of vulnerability assessments, policy decision-makers are limited in their utilization of the results. Hence, a policy-related assessment on thermal environment vulnerability is necessary to allow effective consideration of the thermal environment in policy-making.

In this study, we aimed to propose a way to utilize vulnerability assessment effectively in policy-making by conducting policy-related assessment of the thermal environment. For this purpose, we selected assessment indices by examining previous studies involving the assessment of thermal environment vulnerability in Korea and other countries. We also reviewed the thermal environment improvement policies implemented and planned in Korea to select applicable policies for Korea. Based on the results of this review, we suggested an assessment index-policy linking framework and applied it to Daegu Metropolitan City. Based on the assessment results, we determined the areas that are most vulnerable to the thermal environment and suggested improvement policies for parameters that were the cause of vulnerability. This study shows a method for the strategic application of climate change adaptation policies through policy-related assessment of thermal environment vulnerability, and it is expected to contribute to the effective establishment of thermal environment policies by policy-makers.

2. Materials and Methods

2.1. Study Area

Daegu Metropolitan City in Korea was selected as the study area to investigate the utility of the policy-linked thermal vulnerability assessment. Daegu Metropolitan City is one of the six metropolitan cities in Korea and is located on the Southeastern Korean peninsula (Figure 1). It is a basin structure surrounded by mountains—Mt. Palgong to the Northeast, Mt. Biseul and Mt. Apsan to the south. The total area is 884.1 km^2, of which 798.0 km^2 (90.3%) is urban and 85.6 km^2 (9.7%) is non-urban (Table 1). About 2.5 million people live in Daegu Metropolitan City, which is divided into 8 districts and 139 counties. Six of the districts are 100% urban. Only Dalseong and Donggu include non-urban areas.

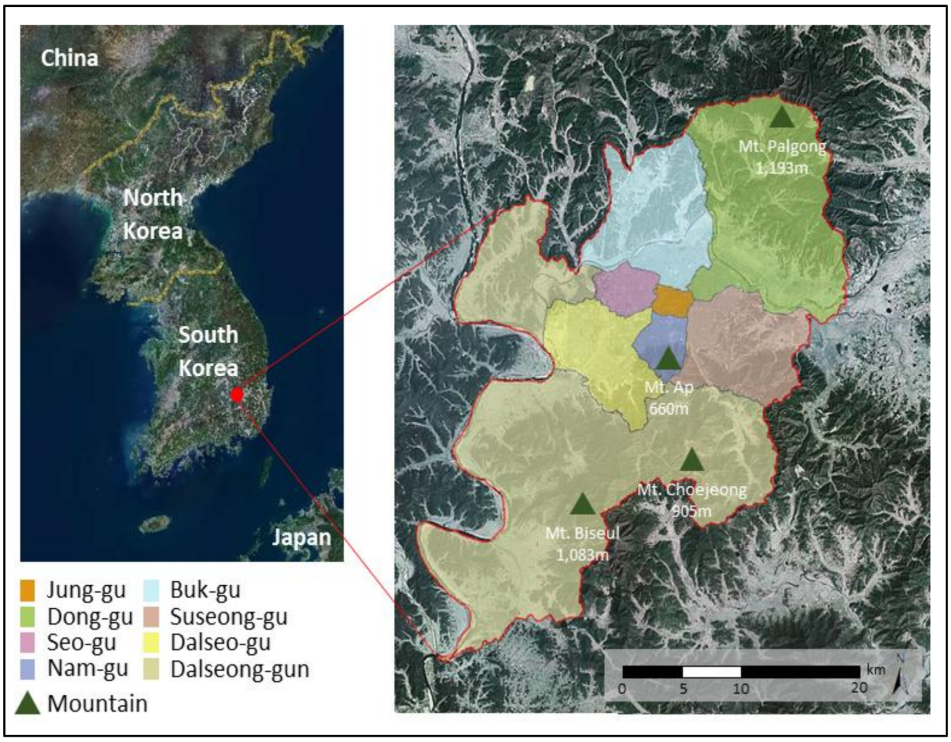


Figure 1. Map of the study area.

Table 1. Urban/non-urban areas in each district of Daegu Metropolitan City.

Category	Urban Area		Non-Urban Area		Sum	
	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (km^2)	Area (km^2)	Ratio (%)
Jung-gu	7.1	100.0	0.0	0.0	7.1	100
Dong-gu	146.9	80.6	35.3	19.4	182.2	100
Seo-gu	17.3	100.0	0.0	0.0	17.3	100
Nam-gu	17.4	100.0	0.0	0.0	17.4	100
Buk-gu	94.1	100.0	0.0	0.0	94.1	100
Suseong-gu	76.5	100.0	0.0	0.0	76.5	100
Dalseo-gu	62.3	100.0	0.0	0.0	62.3	100
Dalseong-gun	376.4	88.2	50.3	11.8	426.6	100
Daegu Metropolitan City	798.0	90.3	85.6	9.7	883.6	100

Among the 17 cities and provinces in Korea, Daegu Metropolitan City is known to be the most vulnerable to heat waves, and its death rate per 100,000 people due to heat is the highest. This city has five automatic climate observation sites that are operated by the Korea Meteorological Administration as infrastructure for measuring the thermal environment. The number of meteorological observation stations is low relative to the area of Daegu Metropolitan City; thus, the thermal vulnerability of Daegu Metropolitan City cannot be identified sufficiently.

2.2. Establishment and Application of an Assessment Index-Policy Linking Framework

The establishment of an assessment index-policy linking framework and its application were conducted in three steps (Figure 2). The first step was to select the assessment indices for thermal environment vulnerability and link them with the thermal environment improvement policy through a literature review. The second step was to evaluate the thermal environment vulnerability of the study area based on the selected indices. The third step was to select vulnerable areas based on the vulnerability assessment results and propose improvement policies based on the causes of the vulnerability.

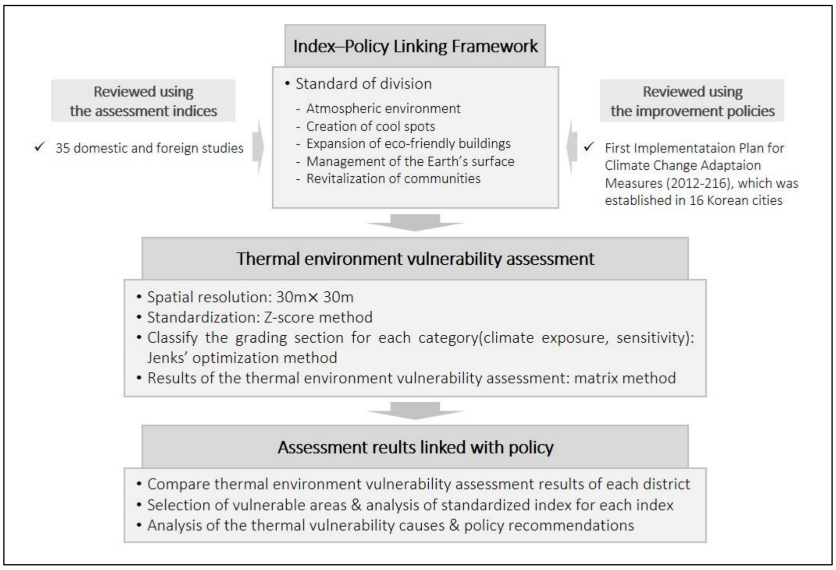


Figure 2. Research process.

2.3. Thermal Environment Vulnerability Assessment

The vulnerability analysis method specified in the "Urban Climate Change Vulnerability Analysis and Usage Guidelines" from the administrative regulation of the Ministry of Land, Infrastructure and Transport was used to assess the thermal environment vulnerability. Local governments in Korea commonly use this method to assess vulnerability owing to climate change. To assess the vulnerability of spatial data established by ArcGIS v.10.2., the following methods were utilized: the Z-score standardization method to directly compare different indices with different measurement units; Jenks optimization method to classify indices using natural breaks in Z-score values; and a simple matrix approach to derive four grades of thermal environment vulnerability based on exposure-related indices (including adaptation-related) and sensitivity-related ones.

2.3.1. Z-Score Standardization

To analyze vulnerability, a standardization process is required that enables direct comparison between different analysis indices with different measurement units. For this purpose, the calculated values utilizing the commonly used Z-score method [20] (Equation (1)) were converted to standardized indices (Equations (2)–(4)), and the values were computed for each grid. Z-scores range from negative to positive values, and the degree of deviation from the mean can be derived from the measured values by setting the standard deviation in units. The standardized index is a value obtained by converting the Z-score to a value between 0 and 1.

$$z_i = \frac{X_i - X_{mean}}{X_{std}} \quad (1)$$

where, Z_i is the Z-score for each zone (i), X_i is the measured value of the analysis index (X) for each zone (i), X_{mean} is the mean of the analysis index (X) for the entire zone, and X_{std} is the standard deviation of the analysis index (X) for the entire zone.

$$Z\text{-}score_{Normal} = a \times z - score + b \tag{2}$$

where $Z\text{-}score_{Normal}$ is the standardized index for each zone (i), and a and b were calculated as follows:

$$a = \frac{1}{(Z\text{-}score_{max}) - (Z\text{-}score_{min})}, \tag{3}$$

$$b = \frac{-Z\text{-}score_{min}}{(Z\text{-}score_{max}) - (Z\text{-}score_{min})}. \tag{4}$$

In this case, $Z\text{-}score_{max}$ is the maximum Z-$score$ value of the entire zone, and $Z\text{-}score_{min}$ is the minimum Z-$score$ value of the entire zone.

2.3.2. Matrix Method

To derive a grade using the matrix method, the standardized indices calculated for each analysis were classified into climate exposure and sensitivity categories according to the IPCC vulnerability concept. The standardized indices for all categories were averaged. The indices corresponding to adaptability were included in the climate exposure category. The natural classification method (Jenks' optimization method) was used to classify the grading section for each category. The analyzed values were classified into grades 1–4. Grade 1 indicates the most vulnerable area. Lastly, the results of the thermal environment vulnerability assessment were derived by the matrix method using the grades in both the climate exposure and sensitivity categories.

3. Results and Discussions

3.1. Policy-Related Vulnerability Assessment of the Thermal Environment

3.1.1. Thermal Environment Improvement Policy

To present the applicable policies in Korea, we reviewed the thermal environment improvement policies presented in the First Implementation Plan for Climate Change Adaptation Measures (2012–2016), which was established in 16 Korean cities. The examined policies were classified into five areas related to the improvement of the thermal environment: improvement of the atmospheric environment, expansion of eco-friendly buildings, management of the surface, creation of cool spots, and revitalization of communities (Table 2). The policies for improvement of the atmospheric environment included securement of a database (such as an expansion of heat wave monitoring systems [21–26], establishment of heat wave and ultraviolet ray research institutes [22], and determination of vulnerable classes to heat waves [27]) and wind path plans [27,28]. To increase the number of eco-friendly buildings, policies for residential environment improvement projects [25,26], cool loops [27,29], green walls [22], etc., were proposed. Management policies for surfaces included expansion into surfaces where evaporation is possible and the amount of heat absorption is low (such as artificial mulching greening projects [25] and the ecological river restoration policy [27,30]). The policies for the creation of cool spots mainly related to the expansion of green areas, such as roadside tree planting [26–28], biotope formation [28], urban forest creation [26–28], ecological park construction [26,27], and rooftop greening [27,31,32]. Lastly, concerning the revitalization of communities, there are support services for vulnerable classes (management of patients with cardiovascular diseases [21,27,33], establishment of monitoring systems for classes vulnerable to the thermal environment [23], help services for the elderly living alone [28,29], and operation of heat wave shelters [25–27]) and policies related to building medical support systems, such as emergency medical support systems and emergency medical service improvement [23,26,34].

Table 2. Policies of Korean local governments aimed at improving the thermal environment based on the Detailed Implementation Plan for Climate Change Adaptation Measures (2012–2016).

Division	Policy	Source
Improvement of the atmospheric environment	Establishment of heat wave warning and alarm systems and monitoring systems	[21–26]
	Establishment of heat wave and UV research institutes	[22]
	Establishment of database on heat wave periods, vulnerable areas, heat wave diseases, and vulnerable classes	[27]
	Wind path creation	[27,28]
Cool spot creation	Urban greening, such as roadside planting	[22,26–28,30]
	Restoration of urban ecosystems, including biotope creation	[28]
	Urban forest creation	[22,26–28,30]
	Ecological park creation	[22,26,27,30,31]
	Rooftop greening projects	[22,26–28,31,32]
	Projects for response of the traditional market to heat waves (cooling fog)	[26]
Expansion of eco-friendly buildings	Improvement of farmhouses, such as attachment of stable ceiling insulators and ventilation facility inspection	[27]
	Housing improvement projects and vacant house maintenance projects	[25,26]
	Cool loop installation	[27,29]
	Wall greening projects	[22]
	Prioritized building greening projects in vulnerable areas	[22]
Management of the surface	Artificial ground greening	[25]
	Ecological river restoration	[27,30]
Revitalization of communities	Improvement of rural medical services	[27]
	Establishment of regional emergency medical care plans and systems	[26,27,33,34]
	Prevention and management of cerebrovascular diseases	[21,27,33]
	Establishment of monitoring systems for health management of vulnerable classes	[23]
	Development of management plans and manuals for each class vulnerable to heat waves	[21,22,25,29,31,33,35]
	Survey of vulnerable classes (preschool children, elderly aged 65 or over, elderly living alone, and other health-vulnerable classes)	[21,23,24,36]
	Management and support for home visits and care	[22,27–29,33]
	Training of helpers for classes vulnerable to heat waves	[22,26,29,36]
	Healthcare services for the elderly in vulnerable classes	[28,29]
	Establishment of an emergency care service system for the elderly living alone	[23,26,27,29,31,35,36]
	Establishment of database on heat wave shelters and selection management	[21–23,25–27,29,31,35]
	Establishment and operation of a task force to manage the situation against prolonged heat waves	[21,26]
	Establishment and promotion of emergency medical support systems	[23,26]
	Customized promotional and educational activities in response to heat waves	[21,24,26,29,31,33]
	Measures for health management in preparation for heat waves	[37]

3.1.2. Selection of Indices for Vulnerability Assessment

To select vulnerability assessment indices, we reviewed 35 domestic and foreign studies on the assessment of thermal environment vulnerability. To link the examined assessment indices with policies, they were divided into five areas: improvement of the atmospheric environment, expansion of eco-friendly buildings, management of the surface, creation of cool spots, and revitalization of communities (Table 3). Improvement of the atmospheric environment included many indices that are directly affected by rising temperatures. In particular, the indices of temperature such as daily maximum temperature and daily minimum temperature have been utilized the most [38–53]. Thermal comfort felt by people living in cities has been utilized as an assessment index for evaluating the thermal environment [44,46,47]. Air pollution factors, such as fine dust and ozone, also were considered as indices [44]. Additionally, the expansion of eco-friendly buildings included indices of buildings that are more sensitive to a deteriorated thermal environment, such as older housing [45,51,54], poor residential areas [14,45,51], and indices of classes that are not actively engaged in economic measures. In the management of the surface, the surface temperature was used as an assessment index [54–57]. The indices regarding ground coverage that increased the temperature of the surface [58–60], such as road ratio, were also utilized. The cool spot creation included measures to reduce temperature or avoid the deteriorated thermal environment in the short and long terms, such as expansion of water and green zones [39,56,61] and wind paths [14], and installations of heat wave shelters [14,53,54] and air conditioners [54,57,60]. Lastly, indices related to age [38–44], poverty [60–62], isolation [38,54,61], disease [54,55,61], health and medical systems [42–44], and municipal finances [42,43,46] were included in community revitalization.

The assessment index–policy linking framework is shown in Table 4. Fifteen indices were selected based on their feasibility as space planning policies. The selected indices were divided into five areas related to the improvement of the thermal environment. The improvement of the atmospheric environment included four indices: daily maximum temperature, daily minimum temperature, thermal comfort (heat index) index, and the air pollution index. In addition, the expansion of eco-friendly buildings had three indices: building surface area, buildings constructed before 1980 when insulation was not legally required, and the number of basic livelihood security recipients. Management of the surface included two indices: road ratio and surface temperature. The creation of cool spots involved one index: the water to green zone ratio. Lastly, the revitalization of communities included five indices: the number of elderly living alone, the number of people aged 65 and over, the number of people aged 5 and under, the number of agricultural workers exposed to harsh outdoor conditions, and the number of cardiovascular disease deaths.

The policies in response to these vulnerability indices included the acquisition of thermal environment observation equipment for improving the air quality, the implementation of alternative-day-no-driving systems during heat waves, the creation of wind paths, the activation of renewable energy, and the supply of electric vehicles. The expansion of eco-friendly buildings included the provision of cool roofs, maintenance of old buildings, wall greening, expansion and maintenance of heat wave shelters, and encouragement to use finishing materials for reducing heat. In addition, the management of the surface included clean-road implementation, concrete pavement block replacement, shade canopy installation, expansion of shade trees, and construction of city water circulation systems using the Low Impact Development (LID) technique. The creation of cool spots included the creation of pocket parks, restoration of rivers, development of road-side strip green belts, expansion of school forest projects, and support for rooftop greening. Lastly, the revitalization of communities included heat wave awareness promotion and educational activities, care for the elderly, maintenance of rural areas, construction of hyperthermia patient monitoring systems, and citizen empowerment. The proposed policies may be supplemented or modified according to the characteristics and circumstances of each local government.

Table 3. Previous studies on thermal environment vulnerability indices.

Division	Index	Foreign																Domestic (Korea)																		
		Vescovi et al. [38]	**Reid et al. [61]**	**Rinner et al. [54]**	**Hondula et al. [58]**	**Chow et al. [39]**	**Tomlinson et al. [55]**	**Loughnan et al. [59]**	**Johnson et al. [56]**	**Wolf et al. [57]**	**Aubrecht et al. [40]**	**Harlan et al. [60]**	**Maier et al. [62]**	**Dong et al. [41]**	**Zhu et al. [42]**	**El-Zein et al. [43]**	**Christenson et al. [44]**	**Seoul Metropolitan City [29]**	**Daegu Metropolitan City [22]**	**Province of Chungcheongbukdo [35]**	**Province of Gyeongsangnamdo [32]**	**Province of Jeollanamdo [25]**	**Gwangju Metropolitan City [23]**	**Province of Gyeongsangbukdo [27]**	**Province of Jeollabukdo [36]**	**Ulsan Metropolitan City [30]**	**Ministry of Land, Infrastructure and Transport [45]**	**Park [46]**	**Jung et al. [47]**	**Koo et al. [48]**	**Ahn et al. [49]**	**Lee et al. [50]**	**Lee et al. [51]**	**Yoo et. al. [52]**	**Shin et al. [53]**	**Eum [14]**
Improvement of the atmospheric environment	Temperature	O				O					O			O	O	O	O	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Fine dust																O																			
	Ozone																O																			
	Thermal comfort																O		√	√	√			√	√	√		√	√		√	√		√		
Cool spot creation	Water and green zones		O			O			O									√				√	√							√			√		√	√
	Wind path																																			√
	Heat wave shelter			O														√																	√	√
	Air conditioners		O	O						O		O								√	√													√		√
Expansion of eco-friendly buildings	Buildings			O														√									√						√		√	√
	Financial factors																	√									√						√		√	√
Management of the surface	Surface temperature			O			O		O	O		O																								
	Land use and coverage				O			O	O			O				O	O			√	√	√	√				√			√	√		√	√	√	√

Table 3. *Cont.*

		Foreign																Domestic (Korea)																		
Division	**Index**	**Vescovi et al. [38]**	**Reid et al. [61]**	**Rinner et al. [54]**	**Hondula et al. [58]**	**Chow et al. [39]**	**Tomlinson et al. [55]**	**Loughnan et al. [59]**	**Johnson et al. [56]**	**Wolf et al. [57]**	**Aubrecht et al. [40]**	**Harlan et al. [60]**	**Maier et al. [62]**	**Dong et al. [41]**	**Zhu et al. [42]**	**El-Zein et al. [43]**	**Christenson et al. [44]**	**Seoul Metropolitan City [29]**	**Daegu Metropolitan City [22]**	**Province of Chungcheongbukdo [35]**	**Province of Gyeongsangnamdo [32]**	**Province of Jeollanamdo [25]**	**Gwangju Metropolitan City [23]**	**Province of Gyeongsangbukdo [27]**	**Province of Jeollabukdo [36]**	**Ulsan Metropolitan City [30]**	**Ministry of Land, Infrastructure and Transport [45]**	**Park [46]**	**Jung et al. [47]**	**Koo et al. [48]**	**Ahn et al. [49]**	**Lee et al. [50]**	**Lee et al. [51]**	**Yoo et. al. [52]**	**Shin et al. [53]**	**Eum [14]**
Revitalization of communities	Activity space														O																				√	
	Poverty	O	O	O	O	O			O	O	O	O	O	O	O	O	O	√	√					√	√	√		√	√	√	√	√	√		√	√
	Age	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	√	√	√	√			√	√	√	√	√	√			√	√	√	√	√
	Isolation	O	O	O	O			O	O		O	O	O			O	O	√						√	√	√	√	√	√	√	√	√	√			√
	Disease		O	O			O			O			O				O		√	√	√			√	√	√		√	√	√	√	√		√	√	√
	Communication (language)	O	O	O	O	O		O	O	O	O	O	O		O	O	O																		√	
	Housing/population density				O		O			O				O		O	O			√	√									√	√		√	√		
	Health and medical														O	O	O	√		√	√			√	√	√		√	√	√		√	√	√		
	Public officials																					√	√										√			
	Local government finance														O	O		√	√	√	√	√	√	√	√	√		√	√				√	√		
	Population less sensitive to heat															O																		√		
	Senior welfare							O									O																			

O: foreign studies, √: Korean studies.

Table 4. Assessment index–policy linking framework.

Category	Vulnerability Assessment Index	Unit	Policy for Improved Thermal Environment
Improvement of the atmospheric environment	Number of days with a daily maximum temperature over 33 °C [a]	Day	Acquisition of thermal environment observation equipment Implementation of alternative-day-no-driving systems during heat waves Creation of wind paths Activation of renewable energy Supply of electric vehicles
	Number of days with a daily minimum temperature over 25 °C [a]	Day	
	PM_{10} (Particuate Matter) concentration [a]	$\mu g/m^2$	
	Thermal comfort (heat index) [a]	Degree	
Creation of cool spots	Water to green zone ratio [c]	%	Creation of pocket parks Restoration of rivers Development of striped green belts by the wayside Expansion of school forest projects Support for rooftop greening
Expansion of eco-friendly buildings	Building surface area [a]	m^2	Provision of cool roofs Maintenance of old buildings Wall greening Expansion and maintenance of heat wave shelters Encouragement to use finish for reducing heat
	Buildings constructed before the 1980s [b]	m^2	
	Number of basic livelihood security recipients [b]	Person	
Management of the surface	Road ratio [a]	%	Clean-road implementation Concrete pavement block replacement Shade installation Expansion of shade trees Construction of water circulation city using the Low Impact Development (LID) technique
	surface temperature [a]	°C	
Revitalization of communities	Number of elderly living alone [b]	Person	Heat wave promotion and educational activities Care for the elderly Maintenance of rural areas Construction of hyperthermia patient monitoring systems Citizen empowerment
	Number of people aged 65 and over [b]		
	Number of people aged 5 and under [b]		
	Number of agricultural workers [b]		
	Number of cardiovascular disease deaths [b]		

[a] Exposure-related index, [b] Sensitivity-related index, [c] Adaptability-related index.

3.2. Thermal Environment Vulnerability of Daegu Metropolitan City

3.2.1. Establishment of Spatial Data for Daegu

A detailed description of the database for each index is shown in Table 5. The data for the assessment was collected through Korean governmental agencies and the US Geological Survey. The spatial resolution of the data for each index was finalized based on a 30 × 30 m grid. The number of days with a daily maximum temperature above 33 °C, the number of days with a daily minimum temperature above 25 °C, and thermal comfort (heat index) were established utilizing the results of the local forecasting model of the Korea Meteorological Administration (LDAPS). Although thermal comfort is a very consolidated topic [63], the choice of a reliable metric for its assessment in urban areas is not an easy issue, due to the need for easy calculation and a reduced number of measurements [64,65]. Not secondarily, most common indices are formulated for specific climatic areas [64]. For the purpose of this investigation, we used the heat index (HI) (°C), a temperature–humidity index formulated by Steadman (Equation (5)) that has been used in previous studies carried out in Korea [66,67] and has been adopted by US National Oceanic and Atmospheric Administration.

$$\begin{aligned} \mathrm{HI} = -42.379 + 2.04901523 \times \mathrm{T} + 10.14333127 \times \mathrm{RH} - 0.22475541 \times \mathrm{T} \times \mathrm{R} \\ -0.00683783 \times T^2 - 0.05481717 \times RH^2 + 0.00122874 \times T^2 \times RH \\ +0.00085282 \times T \times RH^2 - 0.00000199 \times T^2 \times RH^2 \end{aligned} \tag{5}$$

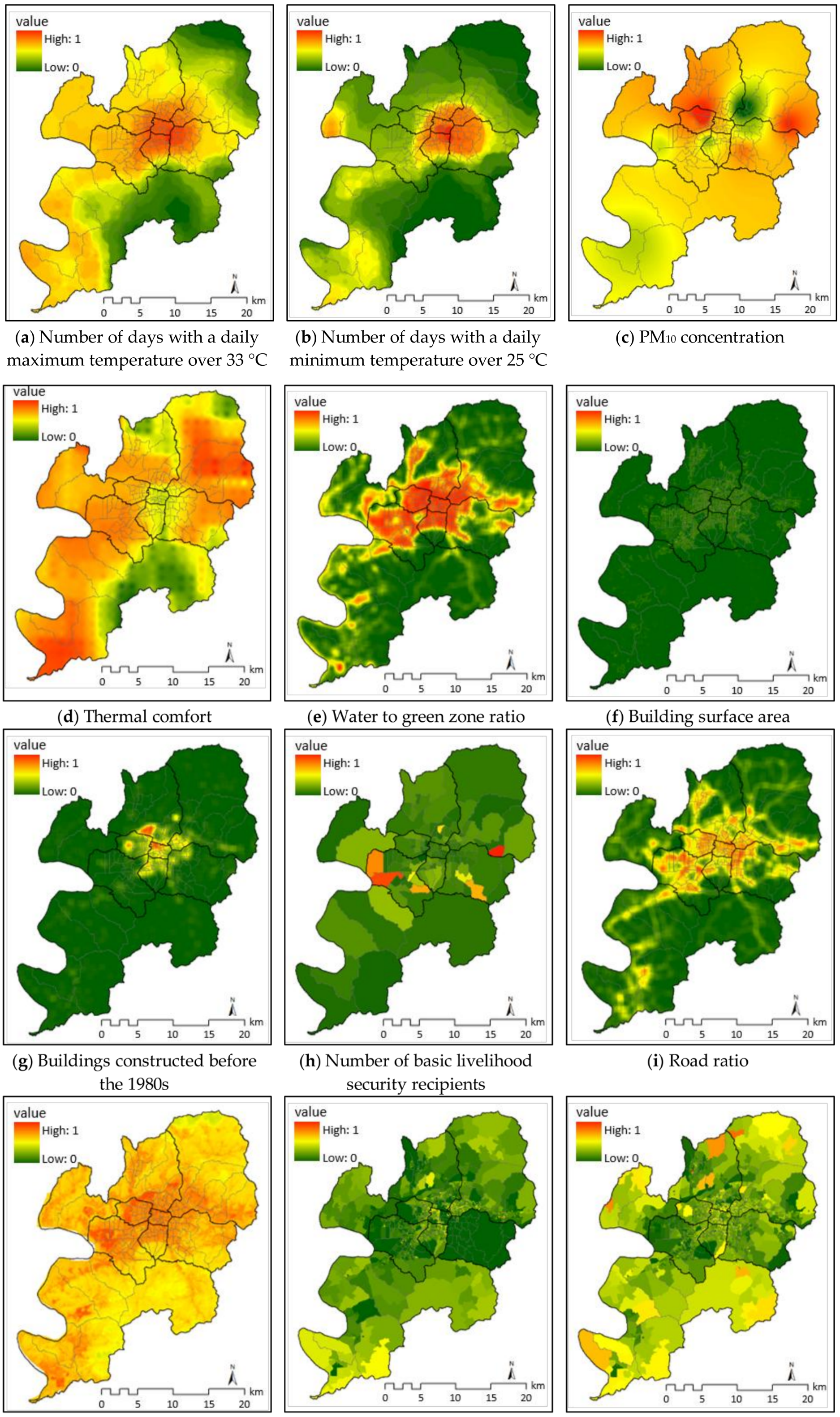
The concentrations of PM_{10} (Particulate Matter) were obtained by using the data from 12 observation sites operated by Air Korean in the Daegu area. The area of water and green zones was extracted from a Ministry of Environment land cover map. The surface areas of buildings and buildings constructed before 1980 were obtained by using the Korea National Spatial Data Infrastructure Portal's GIS building integrated information data. Statistics Korea provided data on the number of basic livelihood security recipients and the number of cardiovascular disease deaths. The road ratio was extracted using the National Geographic Information Institute's continuous topographic map, and the thermal band of Landsat 8 was utilized for surface temperature. The number of elderly living alone, the number of people aged 65 and over, the number of people aged 5 and under, and the number of agricultural workers were obtained through the Soil Groundwater Information System (SGIS).

Table 5. Method for constructing data for analysis indices.

Classification: Strategy	Classification: Index	Resources	Measurement Method and Unit
Improvement of the atmospheric environment	Number of days with a daily maximum temperature above 33 °C (day)	Local forecasting model from the Korea Meteorological Administration (LDAPS) (July–August 2016, 15:00)	Resampling (30 m) after Raster data extraction (2 km)
Improvement of the atmospheric environment	Number of days with a daily minimum temperature above 25 °C (day)	Local forecasting model from the Korea Meteorological Administration (LDAPS) (July–August 2016, 06:00)	Resampling (30 m) after Raster data extraction (2 km)
Improvement of the atmospheric environment	Thermal comfort: Heat Index (degree)	Local forecasting model from the Korea Meteorological Administration (LDAPS) (July–August 2016, 15:00)	Resampling (30 m) after Raster data extraction (2 km)
Improvement of the atmospheric environment	PM_{10} concentration ($\mu g/m^2$)	Air Korea Database (12 stations in the Daegu area)	Interpolation of Geographic Information System (GIS) (Point)
Creation of cool spots	Water to green zone ratio (%)	Land cover map from the Ministry of Environment (2007)	Focal statics of GIS 300 × 300 m (30 × 30 m)
Expansion of eco-friendly buildings	Surface area of buildings (m^2)	Building data from the Korea National Spatial Data Infrastructure Portal	Focal statics of GIS 300 × 300 m (30 × 30 m)
Expansion of eco-friendly buildings	Buildings constructed before the 1980s (m^2)	Building year data from building integrated information (Korea National Spatial Data Infrastructure Portal)	Focal statics of GIS 300 × 300 m (30 × 30 m)
Expansion of eco-friendly buildings	Number of basic livelihood security recipients (person)	Data on each district from Statistics Korea	Counties
Management of the surface	Road ratio (%)	Continuous topographic map (National Geographic Information Institute) road boundary data	Focal statics of GIS 300 × 300 m (30 × 30 m)
Management of the surface	Surface temperature (°C)	Landsat 8 thermal band (13.09.05,14.09.14,14.09.21)	Analysis of thermal band
Revitalization of communities	Number of elderly living alone (persons)	Statistical Geographic Information Service (SGIS) output area unit data	Output area unit (30 × 30 m)
Revitalization of communities	Number of people aged 65 and over (persons)	Output area unit on people aged 65 and over in 2015 Population Census	Output area unit (30 × 30 m)
Revitalization of communities	Number of people aged 5 and under (persons)	Output area unit on people aged 5 and under in 2015 Population Census	Output area unit (30 × 30 m)
Revitalization of communities	Number of agricultural workers (persons)	SGIS output area unit data	Output area unit (30 × 30 m)
Revitalization of communities	Number of cardiovascular disease deaths (persons)	Statistical data on causes of death from Statistics Korea	Districts and provinces

3.2.2. Assessment of Thermal Environment Vulnerability for Daegu

To directly compare different analysis indices with different measurement units, 15 indices were converted to standardized indices using the Z-score method (Figure 3). The standardized indices regarding the number of days with a daily maximum temperature above 33 °C, the number of days with a daily minimum temperature above 25 °C, and buildings constructed before the 1980s were high in Jung-gu, the center of Daegu Metropolitan City. The PM_{10} concentration was high in Northwestern Seo-gu and Southeastern Dong-gu. It was considered that the general industrial complex located in Seo-gu and the Daegu fuel industrial complex in Dong-gu generated significant amounts of PM_{10}. The surface temperature, road ratio, and water to green zone ratio showed high values in the urban areas of Daegu Metropolitan City. The number of agricultural workers was high in Dalseong-gun, which is in the Western part of Daegu Metropolitan City. On the other hand, the number of basic livelihood security recipients, the number of people aged 65 and over, the number of people aged 5 and under, the number of elderly living alone, and the number of cardiovascular disease deaths are demographic and social factors and were distributed throughout Daegu Metropolitan City.



(**a**) Number of days with a daily maximum temperature over 33 °C

(**b**) Number of days with a daily minimum temperature over 25 °C

(**c**) PM_{10} concentration

(**d**) Thermal comfort

(**e**) Water to green zone ratio

(**f**) Building surface area

(**g**) Buildings constructed before the 1980s

(**h**) Number of basic livelihood security recipients

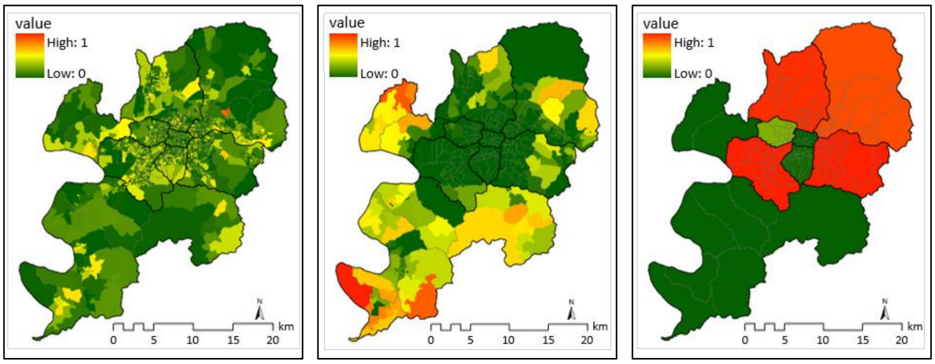
(**i**) Road ratio

(**j**) Surface temperature

(**k**) Number of elderly living alone

(**l**) Number of people aged 65 and over

Figure 3. *Cont.*



(**m**) Number of people aged 5 and under (**n**) Number of agricultural workers (**o**) Number of cardiovascular disease deaths

Figure 3. Thermal vulnerability of each index converted into a standardized index.

The thermal environment vulnerability of Daegu Metropolitan City was classified as grades 1–4 by integrating the individual indices converted into the standardized indices (Figure 4). The distribution of grades for the eight districts in areas and ratios are shown in Table 6. The area with the highest area ratio in the first grade (most vulnerable to heat) was Dong-gu (3.29%), followed by Dalseo-gu (3.28%) and Buk-gu (3.18%). The first-grade regions are located in Southern Dong-gu and in Northern and Southeastern Buk-gu. The first-grade region with the greatest area is Dalseong-gun (10.6 km^2), followed by Dong-gu (5.95 km^2). The reason why Dalseong-gun has a low ratio of first-grade regions relative to its area is that it has a greater non-urban area. The area with the greatest area of fourth-grade regions is Dalseong-gun (40.03%), followed by Dong-gu (37.72%) and Nam-gu (34.29%). The reason why Dalseong-gun and Dong-gu have the greatest area of fourth-grade regions may be that Mt. Biseul and Mt. Palgong occupy a large proportion of the total area. Mt. Apsan accounts for a large percentage of Nam-gu, which is the reason for its high area ratio of fourth-grade regions.

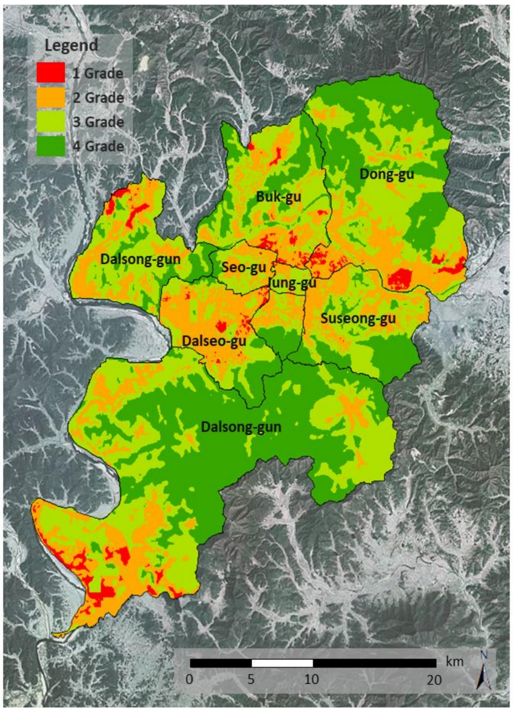


Figure 4. Thermal environment vulnerability assessment results for Daegu Metropolitan City.

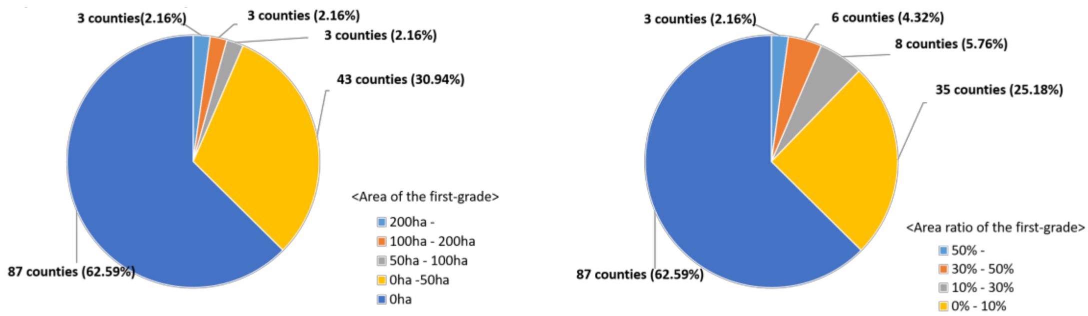
Table 6. Area and area ratio for each thermal environment vulnerability grade in each district.

Category	First Grade		Second Grade		Third Grade		Fourth Grade		Total	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Jung-gu	0.03	0.44	2.15	30.57	4.86	68.99	0.00	0.00	7.04	100
Dong-gu	5.95	3.29	35.98	19.91	70.64	39.08	68.17	37.72	180.74	100
Seo-gu	0.06	0.37	7.76	45.12	7.71	44.87	1.66	9.64	17.19	100
Nam-gu	0.00	0.02	6.22	35.53	5.28	30.16	6.00	34.29	17.49	100
Buk-gu	2.96	3.18	24.09	25.88	42.99	46.17	23.06	24.77	93.11	100
Suseong-gu	0.03	0.03	22.04	28.91	32.68	42.87	21.48	28.18	76.23	100
Dalseo-gu	2.08	3.28	32.11	50.63	19.05	30.04	10.18	16.05	63.42	100
Dalseong-gun	10.60	2.55	77.25	18.57	161.61	38.85	166.55	40.03	416.00	100

3.3. Suggestion for Utilizing Thermal Vulnerability Assessment Linked with Policy

3.3.1. Selection of Vulnerable Areas

The vulnerable areas were selected to identify the causes of thermal environment vulnerability and to suggest policies to mitigate these causes. The area and area ratios of the first-grade regions of the 139 counties in Daegu Metropolitan City were analyzed to select vulnerable areas (Figure 5). The area of the first-grade regions was less than 50 ha in 130 out of 139 counties (93.5%), of which 87 (62.6%) did not include any first-grade regions at all. On the other hand, three counties had more than 200 ha of first-grade regions: Guji-myeon in Dalseong-gun (552.69 ha), Habin-myeon in Dalseong-gun (249.75 ha), and Ansim-1-dong in Dong-gu (242.91 ha) (Figure 5a). Three counties had first-grade area ratios of 50% or more: Ansim-1-dong (70.35%), Sinam-1-dong (63.1%), and Sinam-3-dong (52.23%) (Figure 5b).



(**a**) Area of the first-grade regions (**b**) Area ratio of the first-grade regions

Figure 5. Area and area ratios of the first-grade regions in each county.

Guji-myeon (includes the greatest area of first-grade regions) and Ansim-1-dong (includes the highest area ratio of first-grade regions) were selected as the vulnerable areas. The general characteristics of these areas are shown in Table 7. Ansim-1-dong (D in Figure 6) is 3.5 km^2 in area and has a population of 45,608 (as of 2018), and the Kumho River passes through its Southern section. It is divided into existing housing areas and areas for preparation of new housing sites, and the number of households is increasing according to movement into the new areas. Moreover, a low-income class is concentrated in this area. Guji-myeon (E in Figure 6) is 39.6 km^2 in area and has 6571 inhabitants (as of 2018). In terms of natural environment, Mt. Danni is located in the Northwestern part, and the Nakdong River runs about 15.5 km along the Western boundary. Therefore, it is appropriate land for suburban agriculture.

Table 7. Characteristics of the sample areas.

Category	Ansim-1-Dong	Guji-Myeon
Total area (km^2)	3.45	39.63
Population (person)	45,608	6571
Area of first class regions (km^2)	2.42	5.53
Ratio [(total area/area of the first class regions) × 100%] (%)	70.6	13.9

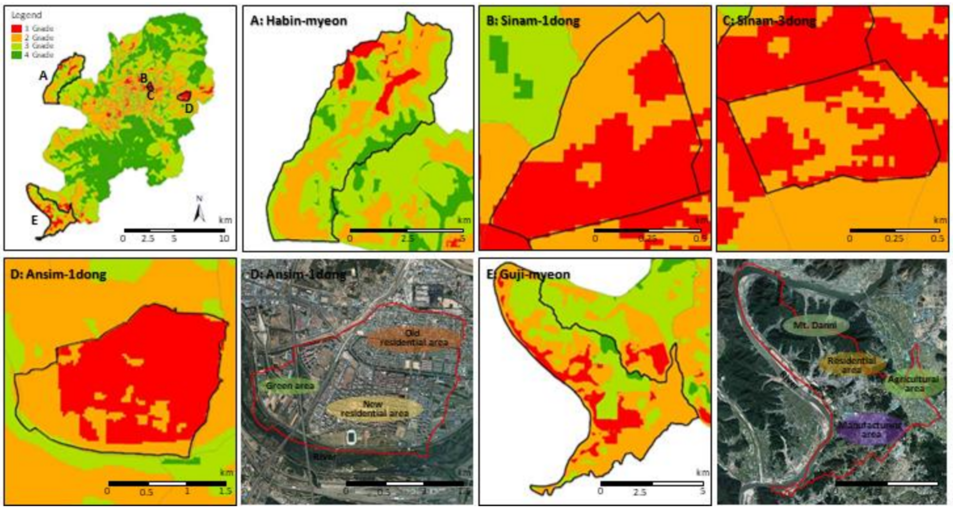


Figure 6. Vulnerability distribution and satellite picture of the sample areas.

3.3.2. Analysis of the Vulnerability Causes and Policy Recommendations

The standardized index for each index of the two areas was calculated to identify the thermal vulnerability causes (Table 8). In the case of Guji-myeon, the standardized index showed the highest value for thermal comfort (0.85), followed by the number of agricultural workers (0.76), temperature of the surface (0.68), and the number of days with a daily maximum temperature above 33 °C. In the case of Ansim-1-dong, the standardized index, from highest to lowest, was as follows: the number of basic livelihood security recipients (0.99), the number of cardiovascular disease deaths (0.79), thermal comfort (0.78), surface temperature (0.75), PM_{10} concentration (0.70), and water to green zone ratio (0.70).

Based on the results of this assessment, it is necessary to more actively implement policies regarding the improvement of the atmospheric environment, management of the surface, and revitalization of communities in Guji-myeon. Maintenance of rural areas, such as through heat wave promotion and educational activities and medical system improvement, should be carried out first for agricultural workers. To improve the surface temperature, policies such as shade installation, expansion of shade trees, and construction of water circulation through the city using the LID technique should be introduced. To cope with the number of days with a daily maximum temperature above 33 °C, policies such as the acquisition of thermal environment observation equipment for monitoring a detailed thermal environment and implementation of alternative-day-no-driving systems during heat waves should be given priority.

To improve the thermal environment vulnerability of Ansim-1-dong, active policy implementation is required in all areas. For basic livelihood security recipients with the highest scores, expansion and maintenance of heat wave shelters is necessary. These individuals face limitations in actively utilizing air-conditioning equipment, such as air conditioners, in a poor thermal environment. Therefore, heat wave shelters installed for the public should be expanded to regions where the population is concentrated. In addition, the equipment in existing heat wave shelters should be maintained. In terms of patients, publicity and educational activities on preventive measures against heat diseases are required. Furthermore, a database for the population with diseases susceptible to high temperature environments should be constructed to establish a hyperthermia patient monitoring system. To lower the surface temperature, concrete pavement blocks should be replaced with heat-reduced pavement blocks. Policies such as "clean-road" in which water is sprinkled on the road during heat waves, shade installation, and expansion of shade trees should be implemented first. To improve the PM_{10} concentration, it is necessary to determine the cause of fine dust. Renewable energy should be activated, and electric vehicle supply should be increased. To increase the water to green zone ratio, it is necessary to expand the green zone. However, it is difficult to secure a large green zone owing to the nature of Ansim-1-dong. Therefore, the creation of pocket parks utilizing leftover space, the development of striped green belts by the wayside, the expansion of school forest projects, and support for rooftop greening should be considered first. Ansim-1-dong has a high level of vulnerability in terms of thermal comfort, so restoration of rivers that may increase humidity should be avoided.

Table 8. Standardized index for each index in vulnerable areas (a high score represents a high level of vulnerability.).

Divison		Guji-Myeon	Ansim-1-Dong
Improvement of the atmospheric environment	Number of days with a daily maximum temperature above 33 °C	0.63	0.53
	Number of days with a daily minimum temperature above 25 °C	0.39	0.32
	Thermal comfort	0.85	0.78
	PM_{10} concentration	0.44	0.70
Creation of cool spots	Water to green zone ratio	0.22	0.70
Expansion of eco-friendly buildings	Surface area of buildings	0.00	0.04
	Buildings constructed before the 1980s	0.01	0.06
	Number of basic livelihood security recipients	0.05	0.99
Management of the surface	Road ratio	0.13	0.51
	Surface temperature	0.68	0.75
Revitalization of communities	Number of elderly living alone	0.40	0.11
	Number of people aged 65 and over	0.51	0.15
	Number of people aged 5 and under	0.12	0.29
	Number of agricultural workers	0.76	0.02
	Number of cardiovascular disease deaths	0.26	0.79

4. Conclusions

In this study, we aimed to propose a way to utilize vulnerability assessment effectively in policymaking by conducting policy-related assessment of the thermal environment regarding worsening urban environmental issues due to climate change. For this purpose, we examined previous studies on the assessment of the thermal environment vulnerability of Korea and other countries. We also reviewed the thermal environment improvement policies that have been implemented and planned in Korea to select applicable policies for Korea. Lastly, we presented a framework consisting of 15 indices in five thermal environment improvement areas (improvement of the atmospheric environment, expansion of eco-friendly buildings, management of the surface, creation of cool spots, and revitalization of communities) and 25 policies.

We analyzed the thermal environment vulnerability in Daegu Metropolitan City. Of the city's eight districts, the region with the highest area of first-grade regions was Dalseong-gun, followed by Dong-gu. The area ratio of first-grade regions was highest in Dong-gu, followed by Dalseo-gu.

The area with the greatest area and area ratio of fourth-grade regions was Dalseong-gun, because its non-urban area is greater than its urban area. Additionally, vulnerable areas were selected for identifying the cause of the thermal environment vulnerability and for suggesting policies. Of the 139 counties in Daegu Metropolitan City, Guji-myeon (the greatest area of the first-grade regions) and Ansim-1-dong (the highest area ratio of the first-grade regions) were selected as the vulnerable areas to investigate. Based on the standardized indices of 15 indices, the causes of the thermal environment vulnerability in the two areas were analyzed. The results showed that Guji-myeon was most vulnerable in terms of thermal comfort, number of agricultural workers, temperature of the surface, and number of days with a daily maximum temperature above 33 °C. Policies such as maintenance of agricultural areas, shade installation, expansion of shade trees, and acquisition of thermal environment observation equipment should be carried out first. Ansim-1-dong showed high thermal environmental vulnerability in the number of basic livelihood security recipients, the number of cardiovascular disease deaths, the thermal comfort, the temperature of surfaces, the PM_{10} concentration, and the water to green zone ratio. Therefore, policies such as the expansion and maintenance of heat wave shelters, establishment of a hyperthermia patient monitoring system, replacement with heat-reduced pavement blocks, shade installation, expansion of shade trees, promotion and provision of electric vehicles, and creation of pocket parks should be implemented first.

This study showed a method for strategic application of climate change adaptation policies using policy-related assessment on thermal environment vulnerability. An economic and institutional feasibility analysis of the results is planned in further study, and it is expected to contribute to the effective establishment of thermal environment policies by-policy makers.

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Author Contributions: Jeong-Hee Eum developed the research framework and wrote the manuscript. Kwon Kim performed research processes. Eung-Ho Jung and Paikho Rho consulted on the data analysis and manuscript development.

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