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Heatwaves at work: Typology and spatial distributions of occupations exposed to heatwaves in Korea

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ABSTRACT

Adapting to heatwaves and other climate change impacts requires identifying vulnerable demographic segments within regions. However, investigations into the spatial distribution of heatwave-vulnerable workers and its implications for local economies have been limited. This study categorizes occupations exposed to heatwaves into five subgroups and analyzes temporal changes in their spatial distributions via a spatial Markov chain model. The results indicate significant heterogeneity in vulnerability among heatwave-exposed occupations, with variations in income, foreign worker proportions, and job instability. The analysis reveals that heatwave-exposed workers are primarily concentrated outside the capital region. Group 3 (manufacturing) exhibited notable industrial clustering, whereas Group 5 (agriculture and fishery) presented high and stable concentrations in rural areas. Conversely, Group 4 (low-skilled and market-sensitive) demonstrates substantial spatial variability. Spatial Markov chain analysis highlights Group 3′s strong agglomeration tendencies influenced by neighboring cities, whereas Group 5 shows minimal spatial effects. Groups 2 and 4 experience considerable shifts in spatial distribution, with Group 2 showing only a 68.7 % probability of sustaining high concentration and Group 4 showing a 62.7 % probability. Recommendations for adaptation strategies and future research related to the economic impacts of climate change are provided on the basis of these findings.

1. Introduction

The increase in the frequency and intensity of heatwaves, droughts, and other climatic extremes in recent decades necessitates strategies to mitigate climate change. Alongside technological and engineering discussions aimed at decelerating this climatic trend, there is a burgeoning interest in scrutinizing the repercussions of climate change on individual well-being and its cascading economic ramifications at national and regional scales (Chambers, 2020; Dell et al., 2012; IPCC, 2023). Projecting the economic damage caused by climate change at the macro and regional levels provides an empirical basis for public and policy discussions on adaptation while also advancing the pursuit of climate justice (Kotz et al., 2024). Such efforts represent proactive responses to the multifaceted impacts of climate change and are in line with the United Nations' Sustainable Development Goals. We also aspire to contribute to such initiatives.

Researchers have empirically estimated the economic impact of heat stress in terms of labor supply, health, and industrial production (Dell et al., 2012; Kjellstrom et al., 2009; Kim & Lee, 2020; Zivin & Neidell, 2014) and have identified occupations threatened by heatwaves and other effects of climate change (Cutter et al., 2003; Nilsson & Kjellstrom, 2010; Gubernot et al., 2014; Schulte et al., 2016). However, little attention has been given to assessing the spatial distribution of vulnerable workers and its implications for local economies. In recognizing the link between health outcomes and individuals' long-term activity patterns, scholars have claimed that it is imperative to account for the dynamic aspects of economic activities, including occupational duties, when evaluating the impact of heatwaves (Gubernot et al., 2014; Nilsson & Kjellstrom, 2010). Furthermore, workers' susceptibility to hazards and their adaptive capacity may vary on the basis of individual workers' socioeconomic, occupational, and physical attributes (Cutter et al., 2003). Effective adaptation to climate change therefore necessitates identifying vulnerable demographic segments within regions and implementing tailored protective measures.

Accordingly, we pursue a dual objective. First, we examined the heterogeneity within the group of workers exposed to extreme heat events during work and categorized these occupations into subgroups via hierarchical clustering on the basis of occupational, environmental,

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and socioeconomic indicators. The aim of this stage is to assess the vulnerability of workers exposed to the threat of extreme heat and to reclassify them on the basis of their type and level of vulnerability. The extent of harm that workers may suffer from heatwaves is determined not only by the level of exposure but also by various demographic, socioeconomic, and occupational factors, such as age, health status, type of contract, and autonomy at work (Cutter et al., 2003; Rey et al., 2009; Schulte et al., 2016). Therefore, even when exposed to the same level of heat, differentiated measures tailored to each type of worker are necessary to increase heatwave adaptability and mitigate potential damage. By establishing a hierarchy within the group of heatwave-exposed workers previously treated as a single entity in earlier studies, this analysis provides an empirical foundation for developing policy responses for each worker group. The central questions in this stage focus on the extent of heterogeneity in vulnerability among heatwave-exposed workers and identify which group is most vulnerable in terms of factors such as economic stability and access to risk-related information.

Second, we investigated the changes in the spatial distribution of these workers from 2010 to 2020 at the city level (*si, gun*, and *gu*) in Korea and identified patterns over the ensuing decade through the application of the spatial Markov chain model. Building on the findings derived from the first stage, this analysis aims to examine the spatial distribution patterns of different groups of workers with varying levels of vulnerability to heatwaves. For example, this study seeks to identify which regions of the country have a high concentration of workers who are particularly vulnerable to heat-related health risks, such as older workers and those in physically demanding jobs. Furthermore, the study investigates whether the proportion of workers vulnerable to heatwaves—especially those with lower job security and income levels—has undergone significant fluctuations over time or remained stable across different cities. The hypothesis to be tested is that the spatial distribution of each worker subgroup, along with their changing patterns, will vary significantly.

As Kim et al. (2016) argued, greater efforts should be made to investigate the concentration of vulnerable jobs and workers, as well as to demonstrate the relationship between this concentration and existing spatial inequalities in opportunities and amenities. As a result of changing conditions such as globalization and deindustrialization, highly skilled, high-income workers, along with various types of urban amenities, tend to concentrate in large cities (Scott, 2010). Consequently, existing spatial inequalities may worsen as the climate crisis intensifies, leading to disproportionately distributed impacts across the country. Korea experienced spatially uneven growth during its industrialization period from the 1960s to the 1980s due to state-led regional development strategies, leading to disparities across various sectors, including industry and employment, education, and public infrastructure. Like many rapidly developed economies in Asia and Europe, Korea's preexisting regional socioeconomic inequalities may overlap with the unequal distribution of heatwave-vulnerable workers, which can significantly undermine the overall welfare of the population. Moreover, in recent years, Korea and the broader Northeast Asia region have experienced unprecedented heatwaves, such as the 2018 heatwave, which led to a surge in heat-related illnesses and widespread livestock deaths, causing serious social issues (Ren et al., 2020). Therefore, the findings of this study on regional heatwave vulnerability not only provide an empirical basis for developing heatwave response strategies and spatial plans in Korea but also offer policy insights and an analytical framework for other countries and regions with similar socioeconomic and climatic characteristics, particularly Northeast and Southeast Asia.

2. Literature review

2.1. Heatwave vulnerability of workers

Climate change vulnerability can be understood as the degree to which a system is sensitive to damage caused by climate variability or extreme weather events, as well as its susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2007, 2023). The concept encompasses the extent to which a system is affected by climate-related stimuli, its potential to mitigate damage, and its capacity to seize opportunities or cope with these challenges. Therefore, even if a system has high levels of exposure and sensitivity to climate change, its overall climate change vulnerability could be considered manageable if it possesses a high adaptive capacity to mitigate the impacts of climate change. Among the impacts of climate change, heatwaves can be considered one of the most crucial impacts that society will face in the future (Klein & Anderegg, 2021; IPCC, 2023); according to the examination of Perkins-Kirkpatrick and Lewis (2020), in almost all regions worldwide, heatwave frequency and cumulative heatwave intensity increased rapidly and greatly from 1950 to 2000. Furthermore, the continuous increase in average temperature and the urban heat island effect may exacerbate the risk of heatwaves (Singh et al., 2017; Wheeler et al., 2019). The potential hazards posed by heatwaves, particularly their socioeconomic ramifications, can affect diverse domains, such as labor, productivity, and crime (Dell et al., 2012; Schulte et al., 2016; Stevens et al., 2019). To address and minimize the risks associated with heatwaves systematically, it is imperative to acquire evidence via empirical research.

Climate change vulnerability does not manifest uniformly across all social strata, and the impacts of climate change can be more severe for regions and communities lacking adequate economic, social, and environmental resources to respond to climate-related stimuli. The identification of populations vulnerable to climate change is often based on biological and socioeconomic factors that influence their health and access to resources (Cutter et al., 2003; Schulte et al., 2016; Mashhoodi, 2021). These include groups with physical limitations, such as children, elderly individuals, people with disabilities, and those with chronic illnesses, as well as socially isolated or resource-poor populations, including low-income individuals and immigrants. With respect to heatwaves, many researchers have identified vulnerable individuals on the basis of a limited set of demographic or socioeconomic characteristics. However, there is a growing recognition of the urgent need to address the impacts on workers in specific industries or occupations, particularly those engaged in outdoor labor, such as agriculture and construction, who are directly exposed to the primary effects of climate change, including heatwaves (Gubernot et al., 2014; Maeda et al., 2006; Schulte & Chun, 2009). Workers exposed to heatwaves experience immediate physiological effects and a reduction in productivity. Additionally, they may endure psychological stress due to income loss caused by work-related hazards, as well as damage to housing and property (Schulte et al., 2016; Tawatsupa et al., 2010).

Working hours constitute a large portion of an individual's daily economic activities, and information about a person's occupation can reflect multiple dimensions in vulnerability assessments, such as economic instability, exposure to environmental risks, and the intensity of physical activities (Kjellstrom et al., 2009). Therefore, considering the work environment and job characteristics when diagnosing an individual's vulnerability to heatwaves is advantageous. Many scholars, including Cutter et al. (2003), Nilsson and Kjellstrom (2010), Gubernot et al. (2014), and Schulte et al. (2016), have contributed to the literature in this area. However, most of these studies focused only on observing and predicting the impacts of climate change on individual workers from an occupational health perspective. Only some researchers have extended their analysis to include spatial dimensions, diagnosing the impacts on local economies and providing evidence for policy measures (Dell et al., 2012; Desbureaux & Rodella, 2019; Kim et al., 2016; Kim & Lee, 2020).

To identify workers affected by heatwaves accurately and estimate the regional scale of impact, it is essential to consider not only their level of heat exposure but also their sensitivity and adaptive capacity. Vulnerable groups such as elderly individuals, immigrants, and women—especially those with poor health, economic distress, or limited bargaining power in the labor market—are particularly susceptible to the effects of climate change (Cutter et al., 2003; Nilsson & Kjellstrom, 2010). Additionally, workers compensated on the basis of output, such as seasonal agricultural laborers, face heightened vulnerability to heatwaves, as they are less likely to take adequate breaks during working hours (Gubernot et al., 2014; Nilsson & Kjellstrom, 2010). This stems from the pressure to meet productivity targets, often leading them to forgo breaks to maintain their earnings. Workers in unstable or temporary jobs are at greater risk of losing employment and suffering economic hardship due to natural disasters (Cutter et al., 2003; Schulte et al., 2016). Similarly, populations with lower levels of education, assets, and income have a reduced capacity to avoid or recover from the impacts of climate change and may lack access to mitigation resources such as insurance and social safety nets (Cutter et al., 2003). Consequently, communities with a high proportion of such individuals may encounter greater difficulties in recovering from heatwaves and other climate-related events.

Many studies have highlighted that outdoor workers engaged in high-intensity physical activities, such as construction laborers and farmers, are more prone to health issues when exposed to extreme heat because of the impaired functioning of the body's cooling mechanisms (Gubernot et al., 2014; Nilsson & Kjellstrom, 2010; Tigchelaar et al., 2020). Workers who work extended hours are also at heightened risk, as fatigue can diminish their ability to respond effectively to heat-related threats, leading to serious harm. Long working hours further increase the duration of exposure to physical and chemical hazards, which are exacerbated by deteriorating working conditions caused by extreme weather, thereby increasing the risk of surpassing permissible exposure limits (Spurgeon et al., 1997; Landsbergis, 2003). According to Gubernot et al. (2014), workers unfamiliar with their work environments are also more likely to experience heat-related injuries. In particular, new employees, who are not yet accustomed to their tasks, face a greater risk of heat-related illnesses (Maeda et al., 2006; Gubernot et al., 2014; Schulte et al., 2016). Nilsson and Kjellstrom (2010) argued that, to enhance the adaptive capacity of these workers and their workplaces, it is crucial to implement educational programs that raise awareness about heat-related risks and provide training on how to mitigate harm during work.

2.2. Adaptation to heatwaves and other climate change impacts

Unlike in the past, when adaptation measures were developed solely on the basis of regional climate scenarios derived through mathematical modeling, recent trends actively incorporated the concept of vulnerability. Climate change adaptation plans and policy measures are now being established with considerations for environmental justice and equity (Ikeme, 2003; IPCC, 2023). Efforts to increase the adaptive capacity of high-risk groups to climate change impacts, such as heatwaves, now involve overlaying nonclimatic and socioeconomic characteristics specific to regions onto future climate scenarios (Adger et al., 2005; Bicknell et al., 2009).

Approaches to assessing climate change vulnerability at the city and regional levels have varied, with discussions on the vulnerabilities of spatial units typically falling into two distinct categories. The first approach, which is predominantly used in urban design and landscape planning, focuses on assessing vulnerability from spatial and infrastructural perspectives, accounting for factors such as land cover, urban morphology, topography, green spaces, and housing conditions (Carter, 2018; Oswald et al., 2020; Litardo et al., 2020). The second approach emphasizes identifying regions with high concentrations of individuals susceptible to climate change impacts on the basis of demographic and socioeconomic characteristics (Chambers, 2020; Kim & Lee, 2020). These vulnerable populations often possess lower physical capabilities, reduced mobility, or limited capacity to adapt to climate-related hazards. Rather than relying solely on one perspective, a growing number of researchers have adopted a comprehensive framework that integrates both spatial-infrastructural and demographic-socioeconomic dimensions to assess regional vulnerabilities (Cutter et al., 2008; Hatvani-Kovacs et al., 2016).

In the past, climate change adaptation policies have been implemented primarily at the national or provincial levels, leading to ambiguity in terms of responsibility and accountability (Amundsen et al., 2010). Top-down, nationally led approaches to climate adaptation have faced challenges such as policy redundancy, procedural complexity, delays in implementation, and difficulties in measuring effectiveness (Adger et al., 2005; Hamin et al., 2014). Since the late 1990s, many countries have shifted climate change response responsibilities to local governments, enabling them to more directly address the specific causes and impacts within their jurisdictions (Wheeler, 2008; Urwin & Jordan, 2008; Baker et al., 2012). Owing to their capacity for flexible and innovative decision-making, local governments have gained significant attention for their role in adaptation and disaster risk management. They are considered more effective at developing tailored adaptation strategies that address the rapid and dynamic nature of climate change (Moser & Luers, 2008; Lawrence et al., 2014). The IPCC (2023) also underscores the importance of local and municipal spatial planning as an effective approach, highlighting the need for inclusive climate governance that engages diverse societal groups.

Fueled by worldwide attention to local responses to climate change, particularly regarding adaptation efforts, climate change governance has emerged in Korea since 1993. Under the Framework Act on Low Carbon and Green Growth (until March 2022; afterward, it was replaced by the Framework Act on Carbon Neutrality and Green Growth for Coping with Climate Crisis), provincial and municipal governments in Korea became responsible for establishing and implementing 'Climate Change Adaptation Action Plans' from 2010 and 2015, respectively. However, several assessment studies conducted in Korea highlight that, for adaptation measures at the local government level to be realistically established and effectively implemented, scientifically derived impact predictions and systematic guidelines for integrating this information should be provided more abundantly (Hyun et al., 2019; Song et al., 2021).

3. Methods

3.1. Categorizing heatwave-exposed occupations

In evaluating heatwave vulnerability levels across occupations in Korea, our initial step involved identifying heatwave-exposed occupations. To identify whether specific workers are exposed to heatwave risks, it is essential to assess not only the extent of their exposure to high temperatures during work but also the degree to which they are exposed to outdoor work environments where mitigating the effects of heatwaves is challenging (Gubernot et al., 2014). We defined heatwave-exposed occupations as those where the average worker both works outdoors and is exposed to extreme temperatures for at least 25 percent of their working hours.[1]

[1] In this study, the term 'heatwave-exposed' should be understood differently from the thermal comfort perspective, as it refers to exposure to high temperatures experienced during work rather than subjective comfort. This study identifies 'heatwave-exposed occupations' based on whether they are exposed to high temperatures during heatwaves, by constructing occupation-specific variables from information on outdoor exposure and extreme temperature exposure. Therefore, caution is needed in interpreting the classification results. It is important to avoid the erroneous assumption that all identified heatwave-exposed occupations are inherently vulnerable or significantly affected by heatwaves from a human biometeorology perspective. The sensitivity of these occupations to heatwave risks and their adaptive capacities will be evaluated and compared during the hierarchical clustering analysis.

To facilitate this identification process, we used the Korea Network for Occupations and Workers (KNOW) survey dataset collected by the Korea Employment Information Service (KEIS). The KNOW survey is conducted annually to collect occupational information, including tasks, requirements, work environments and more; different domains of information are collected each year. In 2018, the survey investigated the work environments and job-related interests of 600 occupations. For each occupation, at least 30 incumbent workers were investigated. The questionnaire included questions about the frequency of outdoor work and exposure to extreme temperatures, temperatures >32 °C or <0 °C. Responses to the questions regarding the frequency of outdoor work and exposure to extreme temperatures during work were measured on a 5-point scale: 'Every day,' 'More than once a week but not daily,' 'More than once a month but not weekly,' 'More than once a year but not monthly,' and 'Never.' Each response was assigned a value of 100, 50, 10, 0, and 0, respectively. Thus, in this study, occupations where workers are exposed to extreme temperatures and engage in outdoor work for an average of five or more days per month were classified as heatwave-exposed occupations.

A limitation of the KNOW data used in this study is its reliance on self-reported information rather than objectively measured indicators of the actual working conditions experienced by workers. For example, the question regarding outdoor work asks for the number of days worked outdoors throughout the year but does not specifically capture whether outdoor work occurred during heatwave periods. To address this, we also considered questions related to the number of days workers were exposed to extreme temperatures in identifying heatwave-exposed occupations. Nevertheless, this approach falls short in accurately measuring the level of thermal comfort experienced by workers, which is influenced by heat exchange with the surrounding environment. Typically, thermal comfort or stress is assessed by considering factors such as humidity, wind speed, and work metabolism. Despite these limitations, the KNOW data remain the only source in Korea that provides detailed information on the working conditions of 600 occupations, offering distinct advantages in terms of representativeness and generalizability compared with thermal comfort data, which can only be gathered through biometeorological sensing devices. As such, these data are highly suitable for the study's objective of quantifying and comparing heatwave exposure and vulnerability across various occupations.

We then assessed the vulnerabilities of heatwave-exposed occupations and categorized the occupations into smaller groups. In this study, referring to the definition of the IPCC (2023), we conceptualized heatwave vulnerability as individuals' propensity or predisposition to be adversely affected by heatwaves or extreme heat events. In accordance with this conceptual framework, we selected twelve variables indicating sensitivity and adaptive capacity vis-à-vis heatwaves, encompassing factors such as age, sex, working hours, job irregularity and instability, educational attainment, income level, nationality, tenure, safety training, and physical task intensity. Appendix 1 presents a detailed explanation of the occupational variables related to heatwave vulnerability for the workers used in this study. Additionally, Section 2.1 provides the theoretical background and a review of previous studies on the relationships between individual characteristics and heatwave sensitivity and adaptive capacity, which form the basis for selecting specific occupational variables.

With a comprehensive set of twelve occupational variables, we conducted hierarchical cluster analysis via Ward's linkage method. In the procedure of hierarchical cluster analysis, each occupation is initially assigned to its own cluster, with subsequent iterative steps merging the two most similar clusters. Through Ward's linkage method, the determination of cluster similarity was measured on the basis of the increase in the sum of squared errors when two clusters were combined (Ward, 1963).

In determining the number of clusters during hierarchical clustering, commonly used methods include calculating the Silhouette coefficient or assessing cluster inertia. The Silhouette coefficient indicates how closely each data point is clustered with others in the same group and how distinctly it is separated from data in other clusters. The coefficient ranges between −1 and 1, with values closer to 1 indicating better clustering. Another method, known as the elbow method, involves evaluating inertia, which is the sum of squared distances from each data point to the centroid of its cluster. This method visualizes inertia across different numbers of clusters, and the optimal number is typically chosen where the rate of decrease in inertia slows, indicating the 'elbow' point. Rather than relying on a single metric, it is advisable to consider multiple indicators and make a comprehensive evaluation when deciding the appropriate number of clusters. In this study, the number of clusters was chosen on the basis of the results of the elbow method and Silhouette analysis, the even distribution of data across clusters, and the similarity and heterogeneity within subgroups.

3.2. Spatial autocorrelation and spatial Markov chain

To identify regions at risk on the basis of the aforementioned categorization, we analyzed the spatial distribution of heatwave-exposed workers across cities and regions in Korea (see Appendix 2). We utilized the Population and Housing Census data from Korea for the years 2010, 2015, and 2020, which are the most recent datasets available following the global economic downturn in the late 2000s. To determine the relative concentrations of specific groups of heatwave-exposed workers, this study utilizes the location quotient (LQ). The LQ is an effective index for analyzing the specialization of jobs and industries within a region and is widely used in regional economic analysis (Billings & Johnson, 2012). Therefore, this index is well suited for the purpose of this study, which is to assess the vulnerability of local labor markets by identifying the concentration of workers susceptible to heatwaves across different regions. We can write the LQ for industry i as below:

$$LQ_i = \frac{e_i/e}{E_i/E}$$

where, e_i represents local employment in industry i, whereas E_i denotes national employment in the same industry. Additionally, e and E refer to total local and total national employment, respectively.

This examination was complemented by a spatial autocorrelation analysis aimed at elucidating whether these workers tended to cluster or disperse. Spatial autocorrelation analysis entails scrutinizing the presence of patterns of similarity or dissimilarity in attribute values, which are contingent upon the spatial proximity of individual entities (Anselin, 1988). The importance of spatial autocorrelation analysis in the context of the distribution of heatwave-vulnerable workers lies in its capacity to provide a quantitative framework for gauging the extent of unevenness characterizing the dispersion of these workers across the country.

The Moran's I for global spatial autocorrelation analysis is derived as follows:

$$Global\ Moran's\ I = \left(\frac{N}{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}}\right)\frac{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

and the local Moran's I_i can be calculated as follows:

$$Local\ Moran's\ I_i = \frac{N(x_i - \overline{x})}{\sum_{i=1}^{N}(x_i - \overline{x})^2}\sum_{j=1}^{N} w_{ij}(x_j - \overline{x})$$

where N is the number of units indexed by i and j, while w_{ij} indicates the spatial weights matrix with zeroes on the diagonal. We used the Queen criterion of contiguity, which treats all regions sharing boundaries as neighbors, to construct spatial weight matrices (w_{ij}). x is the variable of interest, which, in this study, is the proportion of heatwave-exposed workers within a region.

To investigate the patterns of change in the distribution of workers exposed to heatwaves over the past decade, i.e., 2010–2020, we utilized Markov chain models. The classical Markov chain model is a probability model based on the Markov property, which stipulates that the state at a time point depends only on the state at the previous time point. Using past and present information, we constructed a transition matrix to depict the changing patterns and inform our predictions (see Table 1).

In this study, we designated the proportion of workers in heatwave-exposed occupations at the city (*si, gun*, and *gu*) level as the attribute. This matrix enabled us to discern whether areas that exhibited a high proportion of workers in heatwave-exposed occupations in the initial period (2010 or 2015) maintained the same level or transitioned to intermediate or lower levels five years later.

Given the positive spatial autocorrelation observed in the spatial autocorrelation analysis for heatwave-exposed worker proportions, we concluded that the spatial Markov chain models proposed by Rey (2001) represented a more appropriate analytical approach. In the spatial Markov chain model, we considered not only the proportion of heatwave-exposed workers in each city but also the concentration levels of the spatial lags in the initial period. For example, we assumed that several areas that presented the similar concentration level of heatwave-exposed workers in 2010 (2015) may have reached different levels in 2015 (2020) depending on the concentration level of heatwave-exposed workers in neighboring areas. The spatial Markov matrix for the case with three levels is illustrated in Table 2.

The influence of spatial dependence was reflected in the differences between the values in classical Markov chain matrices and their conditioned counterparts in spatial Markov chain matrices. For example, if $m_{HH|H} = m_{HH|M} = m_{HH|L} = m_{HH}$, then regions with a high concentration of vulnerable workers are likely to maintain this high concentration over time, with minimal influence from the concentration levels in surrounding areas; this indicates a lack of spatial dependency. The spatial Markov chain analysis method, which offers the advantage of predicting transition probabilities while accounting for spatial context, is widely applied in analyzing various socioeconomic phenomena, such as regional income disparities (Rey, 2001; Le Gallo, 2004) and changes in industrial location and job distribution (Flores-Segovia & Castellanos-Sosa, 2021).

We focused on 225 cities (municipalities) in Korea, excluding island areas such as Jeju, Seogwipo, and Ulleung. Transition matrices were constructed to encompass changes during two five-year periods: 2010–2015 and 2015–2020. Therefore, analysis was conducted utilizing a total of 450 data points representing state transitions. Individual workers or businesses may have adapted to the intensifying impacts of heatwaves between 2010 and 2020 by either changing career paths or relocating to other cities. However, given Korea's temperate climate, which is characterized by four distinct seasons, the duration of heatwave exposure throughout the year is relatively brief, and regional climatic differences are minimal. As a result, the advantages of relocating within the country to evade heatwaves are limited. While it is conceivable that some heatwave-exposed occupations may be replaced by advanced technologies or by occupations with lower exposure as climate crises intensify in the future, it is anticipated that changes in heatwave frequency and intensity between 2010 and 2020 have had negligible impacts on the relocation of workers and businesses. Instead, it is more likely that most heatwave-exposed occupations have adopted adaptation measures while remaining in their current locations, although the speed of adaptation may vary among workers and businesses. Future research should focus on investigating and analyzing data on adaptation mechanisms specific to various occupations to inform relevant policy implications.

Table 1
. Transition matrix of classical Markov chains.

State t_0	State t_1		
	High	Med.	Low
High	m_{HH}	m_{HM}	m_{HL}
Med.	m_{MH}	m_{MM}	m_{ML}
Low	m_{LH}	m_{LM}	m_{LL}

Table 2
. Transition matrix of spatial Markov chains.

Lag t_0	State t_0	State t_1		
		High	Med.	Low
High	High	$m_{HH\|H}$	$m_{HM\|H}$	$m_{HL\|H}$
	Med.	$m_{MH\|H}$	$m_{MM\|H}$	$m_{ML\|H}$
	Low	$m_{LH\|H}$	$m_{LM\|H}$	$m_{LL\|H}$
Med.	High	$m_{HH\|M}$	$m_{HM\|M}$	$m_{HL\|M}$
	Med.	$m_{MH\|M}$	$m_{MM\|M}$	$m_{ML\|M}$
	Low	$m_{LH\|M}$	$m_{LM\|M}$	$m_{LL\|M}$
Low	High	$m_{HH\|L}$	$m_{HM\|L}$	$m_{HL\|L}$
	Med.	$m_{MH\|L}$	$m_{MM\|L}$	$m_{ML\|L}$
	Low	$m_{LH\|L}$	$m_{LM\|L}$	$m_{LL\|L}$

4. Results and discussion

4.1. Categorizing heatwave-exposed occupations

Among the 600 occupations investigated in the 2018 KNOW survey, 35 were identified as being at high risk of heatwave exposure; the results are presented in Table 3. Among the 35 occupations, one occupation was

Table 3
. Heatwave-exposed occupations by group.

Group	KSCO code	KSCO title
1	236	Fire and emergency management engineers and safety professionals
	411	Police, fire fight and prison related workers
	431	Transport services workers
	620	Forestry related workers
	752	Transport equipment mechanics
	772	Broadcasting and telecommunications equipment related fitters and repairers
	784	Mining and civil engineering related technical workers
	852	Cooling and heating related equipment operators
	881	Water treatment plant operators
2	612	Horticultural and landscape workers
	613	Livestock industry and stockbreeding related workers
	751	Automobile mechanics
	792	Plumbers
	873	Automobile drivers
	874	Handling equipment operators
	875	Construction and mining machines operators
	922	Deliverers
3	741	Die and mold makers, metal casting workers and forge hammersmiths
	742	Pipe and sheet metal makers
	841	Metal casting and metal processing related operators
	842	Painting and coating machine operators
	843	Nonmetal products production machine operators
	876	Ship deck workers and related workers
4	532	Door to door and street sales related workers
	799	Other technical workers
	941	Cleaner and sanitation workers
	953	Sales related elementary workers
	992	Gauge reading, money collecting and parking control related workers
5	611	Crop growers
	630	Fishery related workers
	781	Construction structure related technical workers
	782	Construction related technical workers
	783	Construction finishing related technical workers
	910	Construction and mining elementary workers
	921	Loading and lifting elementary workers

Note: The codes are based on the 7th edition of the Korean Standard Statistical Classification (KSCO) system.

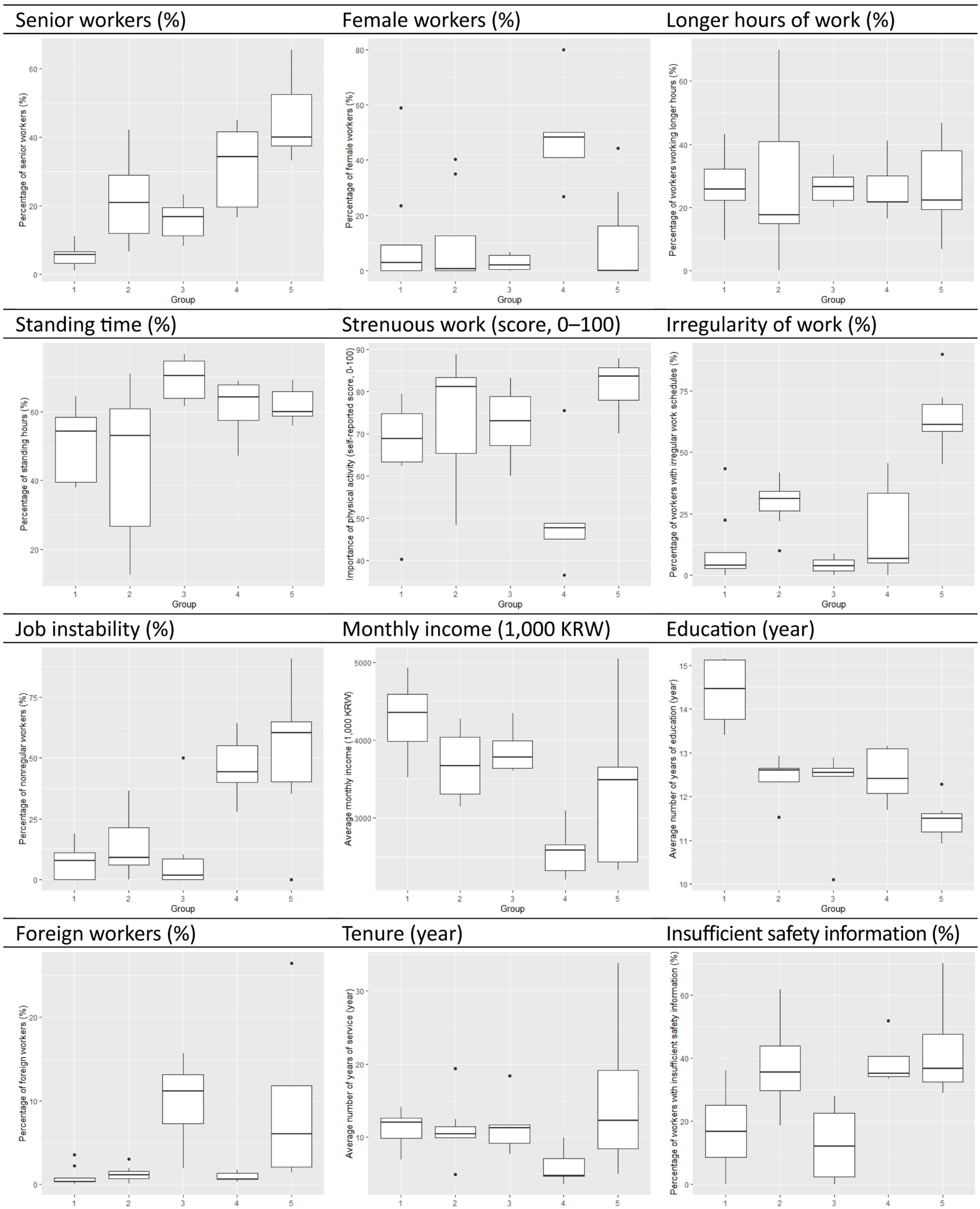

Fig. 1. Box plots of twelve vulnerability indicators for heatwave-exposed occupations by group.

classified under the category of professionals (236), with a Korean Standard Statistical Classification (KSCO) code beginning with 2. Two occupations labeled service workers (411 and 431) and one occupation labeled sales workers (532) were identified as heatwave-exposed occupations. None of the occupations related to managers and clerks, with a KSCO code beginning with 1 and 3, were classified as heatwave-exposed occupations. Conversely, all six occupations of skilled agricultural, forestry and fishery workers were heatwave exposed according to our operational definition. The remaining 26 heatwave-exposed occupations were craft and related trades workers (KSCO code beginning with 7), plants, machine operators and assemblers (8), or elementary workers (9). This finding is consistent with previous research on heatwave vulnerability, which has identified elevated risks in occupations such as construction, agriculture and forestry, metal refining, transportation and logistics, fire and disaster prevention, and hazardous waste management, where workers are typically subjected to prolonged outdoor exposure and a high probability of encountering extreme heat conditions (Schulte & Chun, 2009; Nilsson & Kjellstrom, 2010; Schulte et al., 2016). Notably, the classification outcomes of this study encompass not only conventionally recognized heatwave-exposed occupations but also occupations that have received relatively less attention, such as door-to-door salespersons and street vendors (532), as well as manual laborers involved in fuel station operations, parking management, and utility meter reading for gas, water, and electricity services (953 and 992). Survey data indicate that these occupations generally require >60 % of working hours to be spent outdoors. This newly identified insight highlights the imperative of identifying vulnerable occupations through the integration of both qualitative occupational and industrial information and quantitative data derived from individual-level surveys.

Then, we classified the 35 occupations exposed to heatwaves under the criteria of sensitivity, adaptive capacity, and vulnerability. This classification was achieved through hierarchical cluster analysis, incorporating twelve related occupational variables (see Appendix 1); consequently, we identified five distinct subgroups of heatwave-exposed occupations. According to the Silhouette coefficients derived for different cluster numbers, the highest value was observed with three clusters. The Elbow plot also revealed a significant decrease in the within sum of squares as the number of clusters increased from one to two and then to three. However, when the occupations were categorized into three clusters, the distribution of occupations across the clusters was imbalanced, with 23, 7, and 5 occupations in each cluster (see Appendix 3 for detailed clustering results and metrics). The first cluster, which included 23 occupations, exhibited considerable internal heterogeneity. For example, within the first cluster, 'Fire and emergency management engineers and safety professionals,' who have the highest average educational level among the 35 heatwave-exposed occupations, were grouped together with 'Ship deck workers and related workers' and 'Automobile drivers,' whose average educational levels do not exceed high school graduation. Although the occupations within the first cluster presented similar values for indicators such as job stability and years of service, differences were observed in indicators such as the proportion of foreign workers, the level of safety information provided, and educational attainment. These indicators reflect workers' cognitive levels and response capabilities (Cutter et al., 2003), which significantly affect their vulnerability to heat exposure and must be considered when comparing occupational vulnerabilities and determining the targets of adaptation policies.

Therefore, we decided to classify the heatwave-exposed occupations into five clusters to ensure a more balanced distribution of the 35 occupations across clusters (9, 8, 6, 5, and 7 occupations in each cluster) and to maintain an adequate level of homogeneity within each group. This decision was also based on the assessment that the potential harm—such as the risk of drawing incorrect conclusions or setting misguided policy directions—caused by grouping occupations with different vulnerability-related characteristics into the same cluster outweighs the potential harm of placing occupations that could be grouped together into separate clusters. Notably, when the heat-exposure occupations were categorized into five clusters, the three clusters that had been grouped together as a single cluster under the three-cluster solution—but were separated into Groups 1, 2, and 3 when the five-cluster solution was used—exhibited significantly distinct occupational characteristics, spatial distributions, and patterns of change. A concise overview of each group's characteristics is provided in Fig. 1.

Compared with the other heatwave-exposed groups, Group 1, which included safety professionals, transport equipment mechanics, mining-related technical workers, police, firefighting workers and prison workers, presented higher incomes, advanced education levels, and a lower proportion of nonregular employment, indicating the lowest vulnerability among the five subgroups. Group 2, which included automobile mechanics, plumbers, and delivery drivers, also exhibited a generally low level of vulnerability overall. The noticeable characteristic of Group 3, which included molders, forgers, and sheet metal makers, was the high proportion of foreign workers, nearly 10 %. Additionally, their wages were relatively high, and many of these workers tended to receive appropriate education on safety regulations related to their tasks. They generally represented occupations in the manufacturing sector with high constant demand, although there was also a possibility of decreased employment due to the impact of automation in recent years. Group 4, which included cleaners, sanitation workers, and street sales workers, was characterized by a high percentage of women and elderly individuals, lower income, and a high rate of nonregular employment, rendering it one of the most vulnerable groups to heatwave exposure. Similarly, Group 5, comprising crop growers, fisheries workers, construction laborers, and similar occupations, demonstrated the most irregularity in year-round working hours among the five heatwave-exposed groups, with a high proportion of nonregular workers. This was the group with the lowest education levels and income, followed by Group 4, indicating heightened vulnerability. Despite engaging in physically demanding activities, safety training related to job duties appeared to be less comprehensive for the seven occupations in Group 5.

4.2. The spatial distribution of heatwave-exposed workers

The spatial distribution of workers in occupations exposed to heatwaves, as indicated by the LQ index, is visually represented in Fig. 2. Fig. 2(a) shows the spatial concentration of all workers employed in 35 heatwave-exposed occupations for the years 2010 and 2020. Fig. 2(b) through 2(f) depict changes in the spatial distribution of each subgroup. Additionally, Fig. 3 presents the results of spatial autocorrelation analyses, illustrated with local indicator of spatial association (LISA) maps. Fig. 3(a) shows the results for all heatwave-exposed workers, whereas Fig. 3(b) through 3(f) detail the results for each subgroup.

An analysis of the spatial concentration of overall heatwave-exposed workers in 2010 and 2020 revealed a consistently higher concentration outside both the capital region and metropolitan cities such as Busan, Gwangju, and Daejeon (Fig. 2(a)). The highest concentration of heatwave-exposed workers was observed in Sinan, Jeollanam-do (see Appendix 4 for the list of cities with high or low concentrations of heatwave-exposed workers). In 2020, approximately 67 % of the total workforce in Sinan was engaged in occupations exposed to heatwaves. Overall, areas with high concentrations were predominantly located in Jeollanam-do and Gyeongsangbuk-do in the southwestern and mid-eastern regions of Korea. The LISA map of workers in 35 heatwave-exposed occupations revealed similar patterns to those identified in the LQ distribution. A distinct high-high cluster was observed in

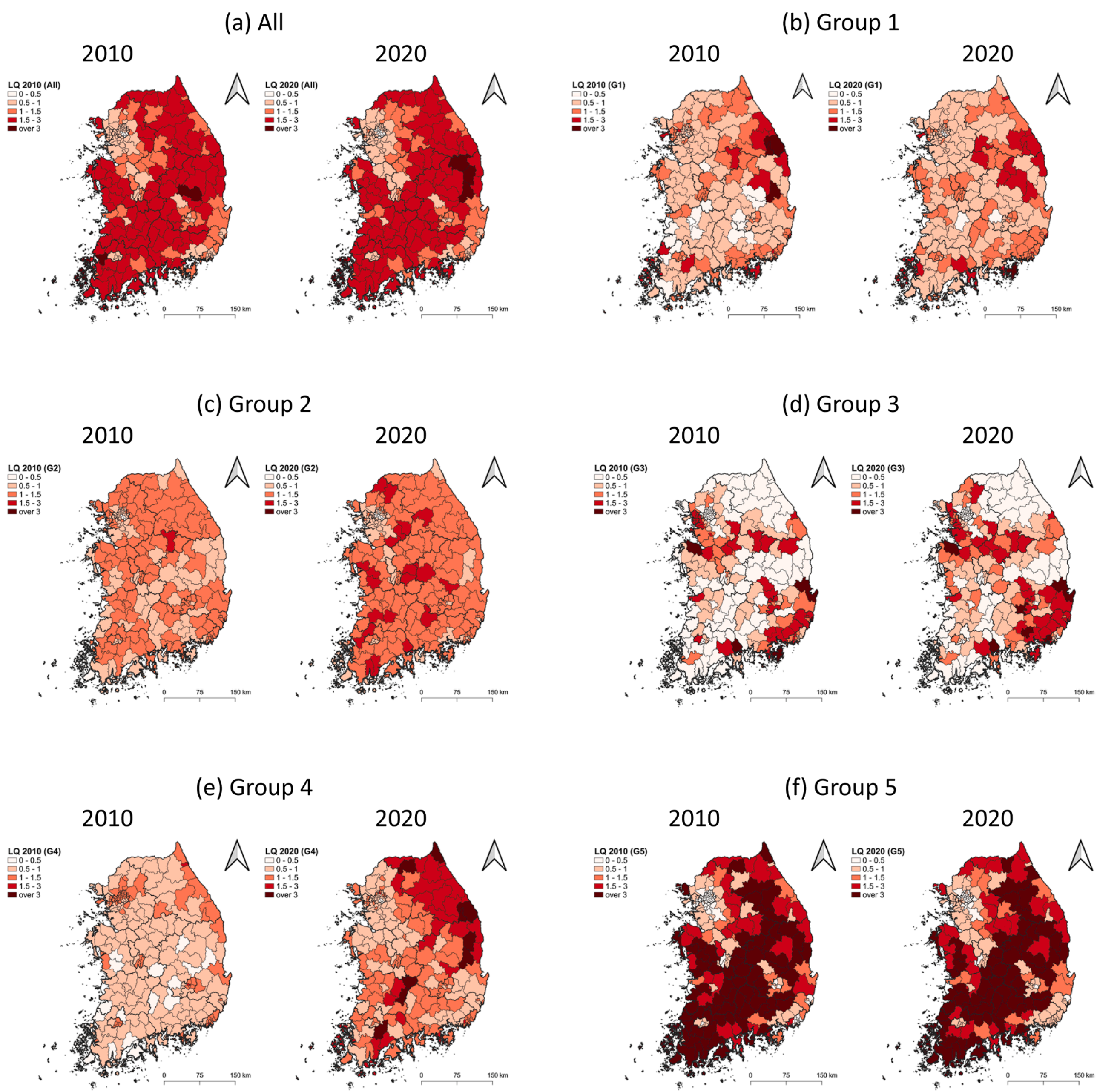

Fig. 2. Location quotients for heatwave-exposed occupations (by group) in 225 cities in Korea, 2010 and 2020.

noncapital cities, whereas a strong low-low cluster was evident in the capital region (Fig. 3(a)). This finding aligns with the results of Kim et al. (2016), who examined the spatial distribution of workers vulnerable to climate change impacts. The uneven distribution of jobs in vulnerable occupations, predominantly in areas outside major cities such as Seoul, Busan, and Gwangju, can be explained by both state-led regional development strategies and the global trend of functional urban specialization (Kim et al., 2016; Duranton & Puga, 2005). However, as discussed in Section 4.1, workers exposed to heatwaves do not constitute a homogeneous group in terms of vulnerability. Therefore, more detailed investigations focusing on specific subgroups are necessary.

Several patterns emerged from the results obtained from the five subgroups. In 2010, Group 1 was relatively concentrated in Gangwon-do, which is in the eastern part of the capital region. However, ten years later, the concentration of Group 1 workers in southern Gangwon-do gradually diminished. This trend likely reflected the decline in coal production, mine closures, and the consequent reduction in related employment opportunities in that region. In 2020, high LQ values were recorded in Geoje, Sinan, and Taebaek; upon examining the proportions, it was noted that they did not exceed 10 % of all workers in those cities, indicating that the concentration was not significant in any area of Korea. Similarly, Group 2 exhibited a comparatively even distribution nationwide, with few spatially distinctive features.

This result may be attributed to the nature of the occupations in Groups 1 and 2—such as police officers and firefighters, fitters and repairers of communication facilities, automobile drivers, and deliverers—where the demand for labor is relatively evenly distributed across the country. These workers are often employed in essential occupations that maintain public infrastructure and basic urban services. Therefore, the high LQ indices for Groups 1 and 2 are likely not due to industrial agglomeration but rather to the relative scarcity of jobs in areas with a weak industrial base, such as the manufacturing and advanced service sectors. As of 2020, Group 1 accounted for only 7.0 % of all heatwave-exposed workers, whereas Group 2 represented 28.4 %, making it the second-largest subgroup after Group 5 (42.9 %). Many occupations in Group 2, including 'Deliverers' and 'Automobile drivers', are characterized by long working hours and limited access to safety information. Long working hours increase workers' exposure to hazards such as heatwaves and, through the accumulation of fatigue, impair their ability to respond swiftly to emergencies (Spurgeon et al., 1997; Landsbergis, 2003). Furthermore, the demand for delivery workers has surged nationwide with the rise of platform labor, yet these workers often lack adequate rest—since they are paid on the basis of the amount of work completed—and are not covered by safety nets such as unemployment insurance. Consequently, it is crucial to develop policy measures and establish a legal framework aimed at improving the working conditions of these heatwave-vulnerable workers.

Conversely, Group 3 displayed a clear spatial concentration in cities such as Gwangyang, Dangjin, and Pohang, which are known for their steel mills and manufacturing complexes. Furthermore, from 2010 to 2020, this group's spatial concentration trend appeared to spread to neighboring regions (Fig. 2(d)). This tendency can be more clearly observed in the LISA map of Fig. 3(d), which depicts the degree of spatial autocorrelation among the workers in Group 3. The results revealed a consistent high-high cluster in Gyeongsangnam-do, including Gwangyang and Pohang. Moreover, a new high-high cluster emerged at Dangjin and Asan, which are approximately 70 kms southwest of Seoul. This clustering tendency reflects the industrial characteristics of the manufacturing sector, which are strongly influenced by the agglomeration of enterprises and employment in terms of productivity (Ellison et al., 2010; Puga, 2010). Furthermore, the high concentration of foreign workers in Group 3 occupations suggests that companies struggling with the labor supply may be strategically located in these areas where a labor pool is established.

These occupations within the metal and nonmetal manufacturing sectors have already garnered attention for their vulnerability to climate change, as the interaction between heat stress and workplace chemicals exacerbates the toxicity of contaminants and heightens the risk of health problems (Bourbonnais et al., 2013; Schulte et al., 2016). However, tailored policy measures and spatial planning implications for these occupations have received minimal attention in the academic literature. Group 3, which was not as highly vulnerable as Groups 4 or 5, was characterized by a high proportion of foreign workers, relatively long working hours, and a high percentage of standing work. Additionally, this group included many occupations likely to face employment reductions due to future task-biased technological changes, indicating its high potential vulnerability. If workers in Group 3 were concentrated in specific cities and their concentration could spread to neighboring areas, adopting a place-based approach and leveraging local knowledge to prepare policy responses might be appropriate. For example, during summer, when the incidence of heat-related illnesses is elevated, additional temporary clinics and enhanced surveillance systems for heat-related ailments could be established in areas with high concentrations of heatwave-vulnerable workers to manage emergency cases. Furthermore, it is imperative to encourage workplaces in affected regions to improve working conditions, particularly by suspending work during heatwaves to mitigate heat-related illnesses. During periods of high heat risk, frequent onsite inspections should be conducted to ensure compliance with established guidelines.

Similarly, Group 5 demonstrated a strong relative concentration during the decade in small towns in Jeollanam-do and Gyeongsangbuk-do, such as Sinan, Cheongsong, and Uiseong. In addition, regarding the LISA map, Group 5 consistently showed widespread high-high clustering in the same area. These results could reflect the characteristics of small rural towns with economies centered on agriculture and fisheries. The occupations in Group 5 are significantly vulnerable to heatwaves across multiple dimensions, including age, work intensity, job insecurity, income, and access to safety information. This indicates the urgent need for heatwave mitigation measures tailored to the local context of these rural towns. In Korea, agricultural and fisheries workers often fall outside the protection of social safety nets, such as insurance for employment injury. Studies have highlighted the health risks these workers face, as well as the associated declines in productivity and income caused by the climate crisis and heatwaves (Tigchelaar et al., 2020). Given that this group faces overlapping social, economic, and environmental vulnerabilities, it is crucial to develop adaptation measures to mitigate heatwave risk. Increasing the enrollment rate of agricultural workers in employment injury insurance through nationwide education and institutional reforms could be beneficial. Furthermore, in regions where vulnerable workers are concentrated, efforts should focus on providing safety training and supplying cooling equipment during heatwaves to prevent heat-related illnesses.

The spatial distribution of Group 4 underwent large changes between 2010 and 2020 and lacked a consistent pattern. This variability could be attributed to the occupations within this group, such as low-skilled jobs related to sales and cleaning, which are susceptible to shifts in market demand on the basis of local conditions. Approaches to heatwave response for these occupations should differ from those in Groups 3 and 5 and align more closely with those for Group 2. The occupations in Group 4, such as 'Door to door and street sales related workers' and 'Cleaner and sanitation workers', often face unpredictable work environments and job insecurity. Additionally, Group 4 has the lowest income levels among the five subgroups. Workers in these conditions are at greater risk of severe economic hardship if they experience health impacts or job loss due to a disaster (Cutter et al., 2003). Furthermore, workers in unfamiliar or uncontrollable environments generally have a diminished capacity to respond effectively to disasters such as heatwaves (Maeda et al., 2006; Gubernot et al., 2014). Given the inconsistent

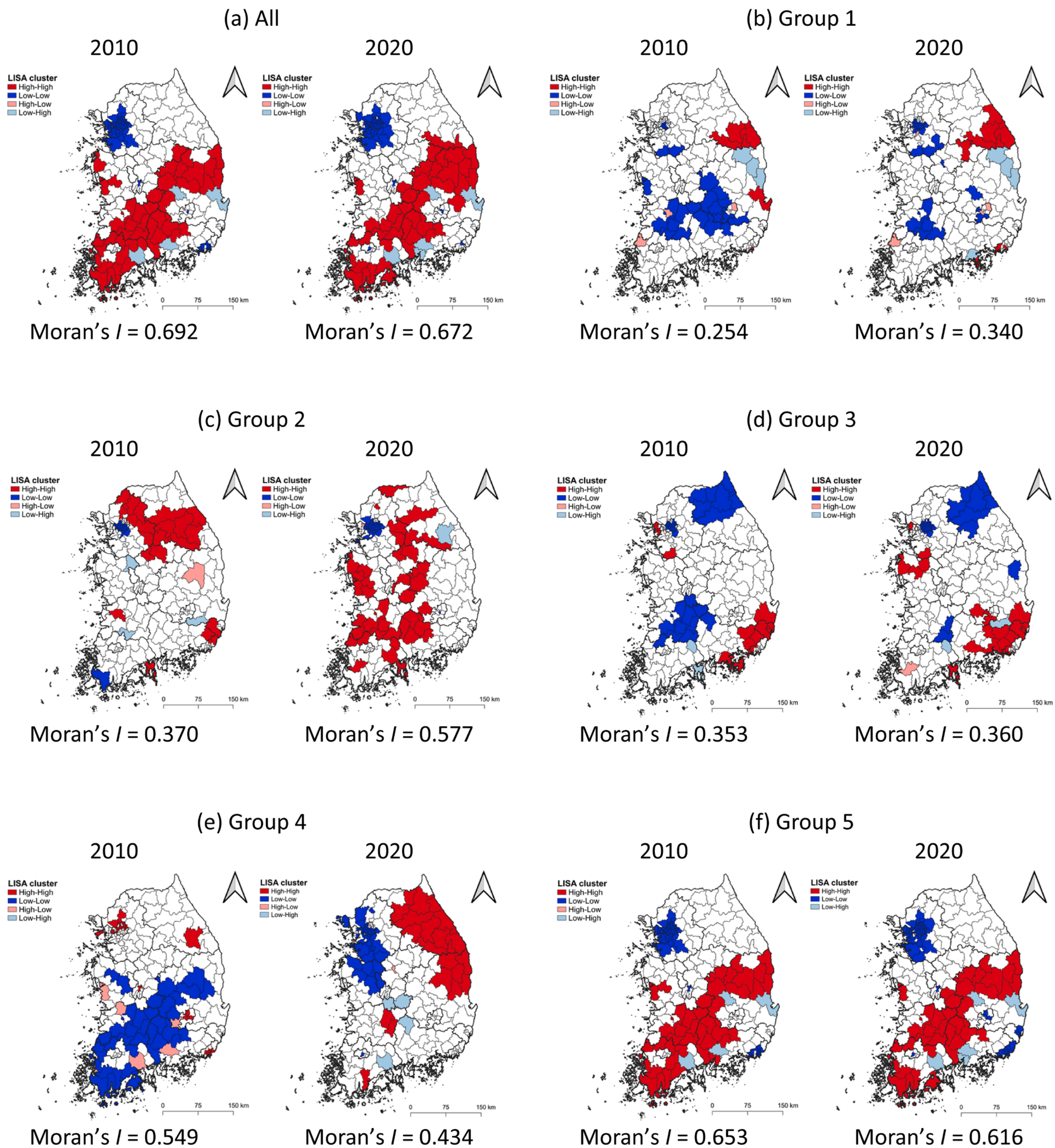

Fig. 3. Local spatial autocorrelation statistics (local Moran's I) for heatwave-exposed occupations (by group) in 225 cities in Korea, 2010 and 2020.

Table 4
. Results of classical Markov chain models, 2010–2015–2020.

State t_0	State t_1								
	All			Group 1			Group 2		
	High	Med.	Low	High	Med.	Low	High	Med.	Low
High	**0.933**	0.067	0.000	**0.800**	0.187	0.013	**0.687**	0.300	0.013
Med.	0.067	**0.833**	0.100	0.180	**0.613**	0.207	0.287	**0.487**	0.227
Low	0.000	0.100	**0.900**	0.020	0.200	**0.780**	0.027	0.213	**0.760**
State t_0	Group 3			Group 4			Group 5		
	High	Med.	Low	High	Med.	Low	High	Med.	Low
High	**0.880**	0.120	0.000	**0.627**	0.260	0.113	**0.953**	0.047	0.000
Med.	0.113	**0.740**	0.147	0.207	**0.507**	0.287	0.047	**0.847**	0.107
Low	0.007	0.140	**0.853**	0.167	0.240	**0.593**	0.000	0.107	**0.893**

Note: The values shown in bold indicate the proportion of regions that remained in the same state over five years.

Table 5
. Results of spatial Markov chain models, 2010–2015–2020.

Lag t_0	State t_0	State t_1								
		All			Group 1			Group 2		
		High	Med.	Low	High	Med.	Low	High	Med.	Low
High	High	**0.959**	0.041	0.000	**0.841**	0.136	0.023	**0.808**	0.192	0.000
	Med.	0.192	**0.808**	0.000	0.268	**0.537**	0.195	0.310	**0.552**	0.138
	Low	0.000	0.000	**1.000**	0.095	0.190	**0.714**	0.000	0.579	**0.421**
Med.	High	**0.852**	0.148	0.000	**0.733**	0.267	0.000	**0.623**	0.377	0.000
	Med.	0.057	**0.852**	0.091	0.172	**0.672**	0.155	0.300	**0.450**	0.250
	Low	0.000	0.171	**0.829**	0.021	0.167	**0.812**	0.108	0.324	**0.568**
Low	High	**0.500**	0.500	0.000	**0.765**	0.235	0.000	**0.458**	0.458	0.083
	Med.	0.000	**0.806**	0.194	0.118	**0.608**	0.275	0.219	**0.438**	0.344
	Low	0.000	0.080	**0.920**	0.000	0.222	**0.778**	0.000	0.096	**0.904**
Lag t_0	State t_0	Group 3			Group 4			Group 5		
		High	Med.	Low	High	Med.	Low	High	Med.	Low
High	High	**0.913**	0.087	0.000	**0.649**	0.225	0.126	**0.975**	0.025	0.000
	Med.	0.184	**0.789**	0.026	0.303	**0.394**	0.303	0.103	**0.828**	0.069
	Low	0.000	0.333	**0.667**	0.333	0.167	**0.500**	0.000	1.000	**0.000**
Med.	High	**0.833**	0.167	0.000	**0.545**	0.364	0.091	**0.857**	0.143	0.000
	Med.	0.063	**0.810**	0.127	0.176	**0.527**	0.297	0.041	**0.856**	0.103
	Low	0.028	0.222	**0.750**	0.163	0.140	**0.698**	0.000	0.160	**0.840**
Low	High	**0.727**	0.273	0.000	**0.667**	0.333	0.000	**1.000**	0.000	0.000
	Med.	0.152	**0.515**	0.333	0.186	**0.558**	0.256	0.000	**0.833**	0.167
	Low	0.000	0.095	**0.905**	0.158	0.287	**0.554**	0.000	0.089	**0.911**

Note: The values shown in bold indicate the proportion of regions that remained in the same state over five years.

spatial patterns observed in Group 4, implementing legislative measures aimed at improving overall working conditions and environments for these workers may be more effective. This should include policies such as guaranteeing the right to cease work during heatwaves, adjusting workloads, and ensuring adequate staffing.

4.3. The patterns of changes in the spatial distribution of heatwave-exposed workers

The changing patterns identified in Section 4.2 were further examined via classical Markov chain models, as presented in Table 4. The results for Groups 3 and 5 indicate that their concentration levels—-whether high, medium, or low—remained stable in most regions over a five-year period. For example, cities with a high proportion of Group 3 and Group 5 workers in the initial year (2010 or 2015) had probabilities of 88.0 % and 95.3 %, respectively, of maintaining their state. In cities with low concentration levels, the probabilities of maintaining their state were 85.3 % and 89.3 %, respectively, whereas in cities with medium-level concentrations, the probabilities were 74.0 % and 84.7 %, respectively. Overall, regions in the medium-level group presented slightly higher transition probabilities, either upward or downward.

Conversely, Groups 2 and 4 exhibited significant transitions in worker concentration levels across cities. For example, cities with a high concentration of Group 2 workers in the initial year had only a 68.7 % probability of maintaining that level after five years, with 30.0 % and 1.3 % probabilities of dropping to medium- or low-level concentrations, respectively. The transition was even more pronounced for Group 4, where only 62.7 % of high-concentration cities maintained their position over five years, while 26.0 % transitioned to the medium level and 11.3 % to the low level. This finding supports the research hypothesis proposed in this study, which suggests that significant differences exist in the spatial distribution and changing patterns within the group of heatwave-exposed occupations. As previously noted, these differences can be attributed to the locational characteristics of industries related to certain occupations (Groups 3 and 5) and the persistence or recent shifts in labor demand (Groups 1, 2, and 4).

In this study, spatial Markov chain analysis was employed to evaluate the spatial autocorrelation within each subgroup of heatwave-exposed occupations, with the specific aim of assessing the extent to which worker concentration in a given area is influenced by the conditions of neighboring cities. Before conducting spatial Markov chain analyses, the relevance of incorporating proximity effects in examining

Table 6
. Number of state-lag cases by group, 2010 and 2015.

State	Lag	All	Group 1	Group 2	Group 3	Group 4	Group 5
High	High	**121 (26.9)**	**88 (19.6)**	**111 (24.7)**	**120 (26.7)**	**103 (22.9)**	**73 (16.2)**
	Med.	27 (6.0)	45 (10.0)	33 (7.3)	28 (6.2)	36 (8.0)	53 (11.8)
	Low	2 (0.4)	17 (3.8)	6 (1.3)	2 (0.4)	11 (2.4)	24 (5.3)
Med.	High	26 (5.8)	41 (9.1)	33 (7.3)	29 (6.4)	38 (8.4)	58 (12.9)
	Med.	**88 (19.6)**	**58 (12.9)**	**74 (16.4)**	**97 (21.6)**	**79 (17.6)**	**60 (13.3)**
	Low	36 (8.0)	51 (11.3)	43 (9.6)	24 (5.3)	33 (7.3)	32 (7.1)
Low	High	3 (0.7)	21 (4.7)	6 (1.3)	1 (0.2)	9 (2.0)	19 (4.2)
	Med.	35 (7.8)	48 (10.7)	43 (9.6)	25 (5.6)	36 (8.0)	37 (8.2)
	Low	**112 (24.9)**	**81 (18.0)**	**101 (22.4)**	**124 (27.6)**	**105 (23.3)**	**94 (20.9)**
Total		450 (100.0)	450 (100.0)	450 (100.0)	450 (100.0)	450 (100.0)	450 (100.0)

Note: Percentages in parentheses. The values shown in bold indicate the cities that share the same state as their neighboring cities.

the changing patterns of worker concentration can be evaluated via Moran's *I* indices. As shown in Fig. 3, all the subgroups of heatwave-exposed occupations presented positive global Moran's *I* values. The global Moran statistics for Groups 2, 4, and 5 were particularly high, with values of 0.577, 0.434, and 0.616, respectively, in 2020. These findings suggest that applying a spatial Markov chain model, which accounts for potential spatial autocorrelation in the distribution of workers, would be beneficial for this study. The spatial Markov matrices for overall heatwave-exposed workers and each subgroup, accounting for the concentration levels in neighboring cities, are shown in Table 5. By comparing the results of Tables 4 and 5, we were able to analyze the impact of spatial lag.

The transition patterns for Group 2 were distinctive; areas surrounded by cities with high concentration levels were more likely to experience an increase in their own concentration level. For example, cities with medium- and low-level concentrations of Group 2 workers neighboring high-concentration areas had probabilities of 31.0 % and 57.9 %, respectively, of moving to a higher concentration level. Conversely, if neighboring areas had a low concentration of Group 2 workers, the likelihood of a decrease in concentration was significant. A substantial proportion of cities with high- (45.8 %) and medium-level (34.4 %) concentrations of Group 2 workers shifted to medium- and low-levels when surrounded by low-concentration cities. Since the majority of Group 2 workers are employed in transportation-related occupations—such as automobile drivers (54.5 % of all Group 2 workers in 2020), deliverers (14.4 %), and automobile mechanics (8.8 %)—their spatial distribution is not closely linked to industrial agglomeration. As discussed in Section 4.2, the high proportion of Group 1 and 2 workers is better interpreted as reflecting the weak industrial base of these cities. While the transition probabilities of Group 1 were not as pronounced as those of Group 2, they remained above the overall average. These results suggest that the recent concentration of resources and human capital in major cities, including capital regions, may have weakened the industrial base in most small and medium-sized cities in Korea.

The tendency for agglomeration was particularly evident in Group 3. Cities with low concentrations of Group 3 workers in neighboring areas had a significantly greater likelihood of experiencing a decline in concentration levels over five years. Conversely, if neighboring cities had high concentrations of Group 3 workers, the likelihood of an increase in concentration in the target city was elevated. The probabilities of cities with high concentrations of Group 3 workers shifting to lower levels varied significantly depending on their surroundings: 8.7 % for cities neighboring high-level concentration areas, 16.7 % for those surrounded by medium-level cities, and 27.3 % for cities neighboring low-level concentration areas. Similarly, cities with low concentrations of Group 3 workers were influenced by the concentration levels of their neighboring cities. For example, 33 % of cities adjacent to high-concentration neighbors moved to higher concentration levels over five years, whereas only 9.5 % of cities neighboring low-concentration areas moved.

Both Fig. 3 and Table 6 indicate a strong reinforcement effect of concentration. Table 6, which displays the distribution of cities and their neighboring cities by concentration level, reveals that cities with high Group 3 worker concentrations were frequently surrounded by other high-concentration cities (26.7 %), whereas cities with low worker concentrations often clustered with other low-concentration cities (27.6 %). This pattern reflects the effects of agglomeration economies, where the economic benefits of clustering are particularly pronounced in sectors such as manufacturing (Ellison et al., 2010; Puga, 2010).

In the classical Markov chain analysis, Group 5, like Group 3, demonstrated a tendency for worker concentration levels to remain stable over a five-year period. However, a distinct characteristic of Group 5, compared with Group 3, was the significantly larger number of regions where worker concentration levels remained unchanged, with little influence from spatial lags. For example, if a city initially exhibited a high-level concentration of Group 5 workers, there was a strong likelihood of maintaining this level over five years, regardless of whether the concentration levels in neighboring cities were high (97.5 %), medium (85.7 %), or low (100.0 %). This result can be interpreted as reflecting the fact that, unlike Group 3—comprising mostly manufacturing jobs, where capital investment heavily influences industrial location and job distribution—Group 5 includes agricultural and fisheries occupations, which are less mobile, and the natural environment plays a crucial role in job location. These findings suggest that heatwave adaptation measures for Group 3, where the distribution of workers tends to spread to surrounding areas over time, may be more effective if future changes in local economic conditions are considered. In contrast, heatwave mitigation strategies for Group 5 may benefit from long-term spatial planning on the basis of a detailed analysis of current conditions.

The spatial distribution of Group 4 workers fluctuated the most over five years among the five subgroups, according to both the classical and spatial Markov chain analysis results. There was a considerable change in the concentration levels of Group 4 workers, and no clear trend was observed concerning the conditions of neighboring cities. In all the cases, the probability of maintaining the concentration level of Group 4 workers over five years did not exceed 70 %. The likelihood of either a one-level decrease or increase in concentration levels was evenly distributed, ranging from 14 % to 36 %. As mentioned earlier, for these workers, a place-based policy approach may not be suitable, and there is a need to promote institutional and legislative changes.

This study concentrated on the vulnerability of workers in Korean cities and sought to derive implications for labor policy. Consequently, it does not encompass all the dimensions of regional heatwave vulnerability. A comprehensive assessment of regional heatwave vulnerability would benefit from considering both the physical environment, such as land cover and microclimate, and aspects of adaptive capacity, including administrative efficiency and the availability of heatwave shelters. Future research should aim to develop a robust evaluation framework that incorporates a range of indicators, including the proportion of heatwave-vulnerable workers, to fully capture regional heatwave vulnerability.

5. Conclusions

In regions such as Korea, characterized by spatially uneven development and escalating regional disparities, the impacts of climate crises—including heatwaves—have the potential to exacerbate preexisting inequalities. Therefore, it is imperative to undertake a comprehensive analysis of the current situation and project potential economic damage to regional economies. This study categorizes occupations exposed to heatwaves into distinct subgroups and employs a spatial Markov chain model to analyze the evolution of their spatial distribution over a decade.

The analysis reveals substantial heterogeneity in vulnerability among the 35 heatwave-exposed occupations, particularly with respect to attributes such as income levels, the proportion of foreign workers, and job stability. The application of the LQ index and LISA maps reveals that heatwave-exposed workers are predominantly concentrated outside the capital region. Specifically, Group 3, associated with manufacturing, exhibits notable industrial clustering, indicative of significant agglomeration effects. Conversely, Group 5, representing occupations in rural areas dependent on agriculture and fisheries, shows high concentrations within these locales. In contrast, Group 4, encompassing low-skilled, market-sensitive occupations, displays considerable spatial variability.

Spatial Markov chain analysis, corroborated by high Moran's *I* values, underscores Group 3′s pronounced agglomeration tendencies, with its spatial concentration being significantly influenced by neighboring cities. Owing to its rural and sector-specific nature, Group 5 has minimal spatial influence. In contrast, Groups 2 and 4 experienced substantial shifts in spatial distribution, with Group 2 maintaining only a 68.7 % probability of sustaining high concentrations and Group 4 maintaining a mere 62.7 %. This variability highlights the necessity for policy interventions and legislative reforms that extend beyond localized strategies. Conversely, heatwave adaptation measures for Groups 3 and 5 may benefit from long-term spatial planning informed by a detailed analysis of current conditions and future projections.

The differential vulnerability to heatwaves among various occupations—despite similar exposure levels—and the spatial unevenness of these vulnerable occupations suggest that the scale of economic damage, including decreased productivity and increased industrial accidents, may vary spatially as climate change intensifies and extreme weather events become more frequent. The analytical approach employed in this study, which maps spatial change patterns of worker groups via the Markov chain model, is applicable to other research areas concerning vulnerable populations. This framework may prove valuable for identifying spatial patterns of workers affected by other natural disasters, such as cold waves or floods, as well as those impacted by technological advancements, such as automation and artificial intelligence.

This study has concentrated on the indirect economic impacts of heatwaves, such as health deterioration and reduced worker productivity, while excluding direct impacts such as crop production losses and broader industrial shifts. Future research should incorporate these dimensions to provide a comprehensive assessment of the economic impact of heatwaves on regional economies and labor markets. Despite its limitations, this study contributes to the literature by examining the economic activities of residents through their occupational vulnerabilities, thereby offering a more nuanced understanding of the impacts of heatwaves. The findings are anticipated to advance the discourse on the multidimensional effects of climate change and stimulate further research in related fields.

CRediT authorship contribution statement

Sangyun Jeong: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Hanna Kang:** Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Minjin Cho:** Writing – original draft, Data curation, Conceptualization. **Up Lim:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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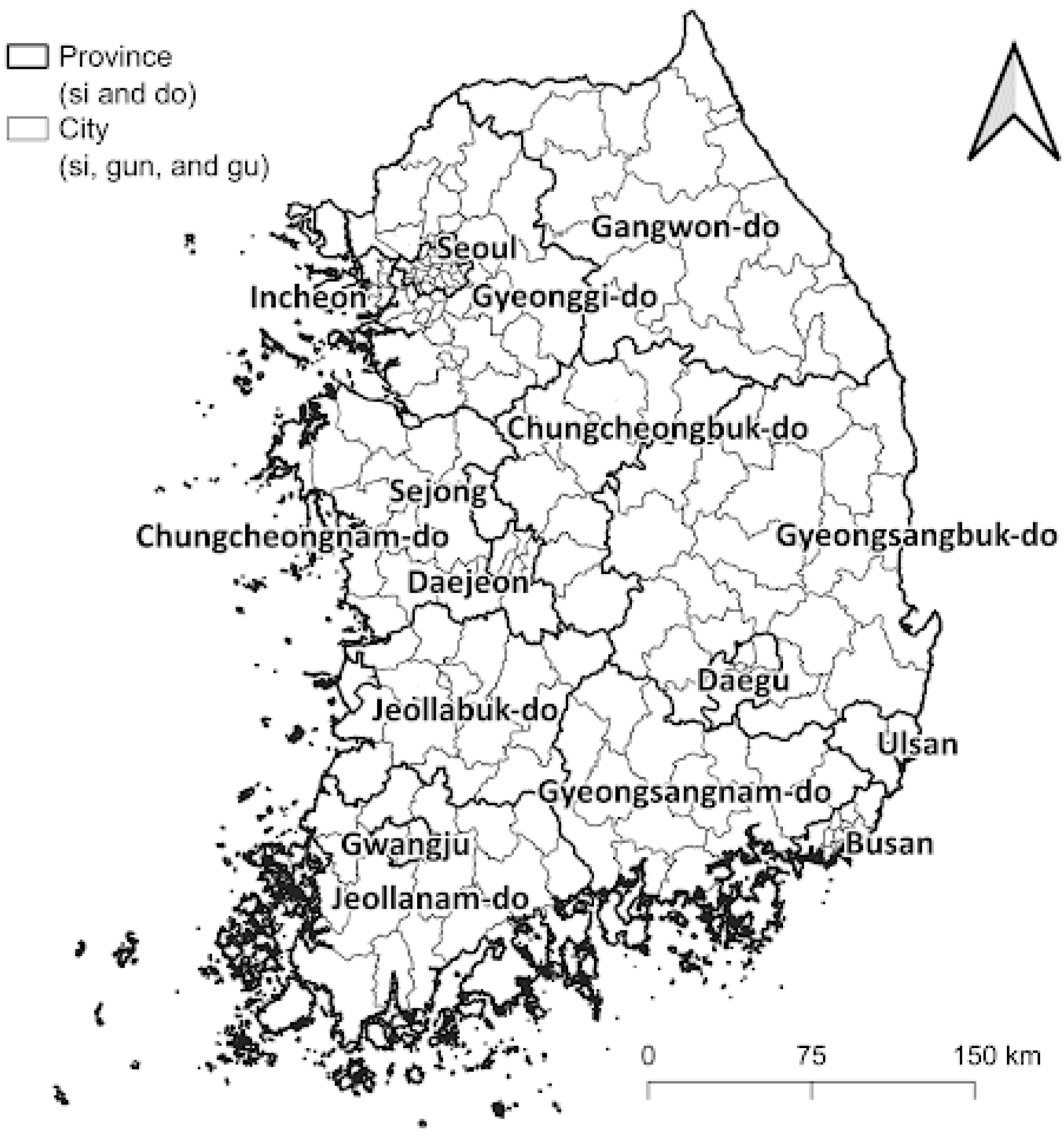
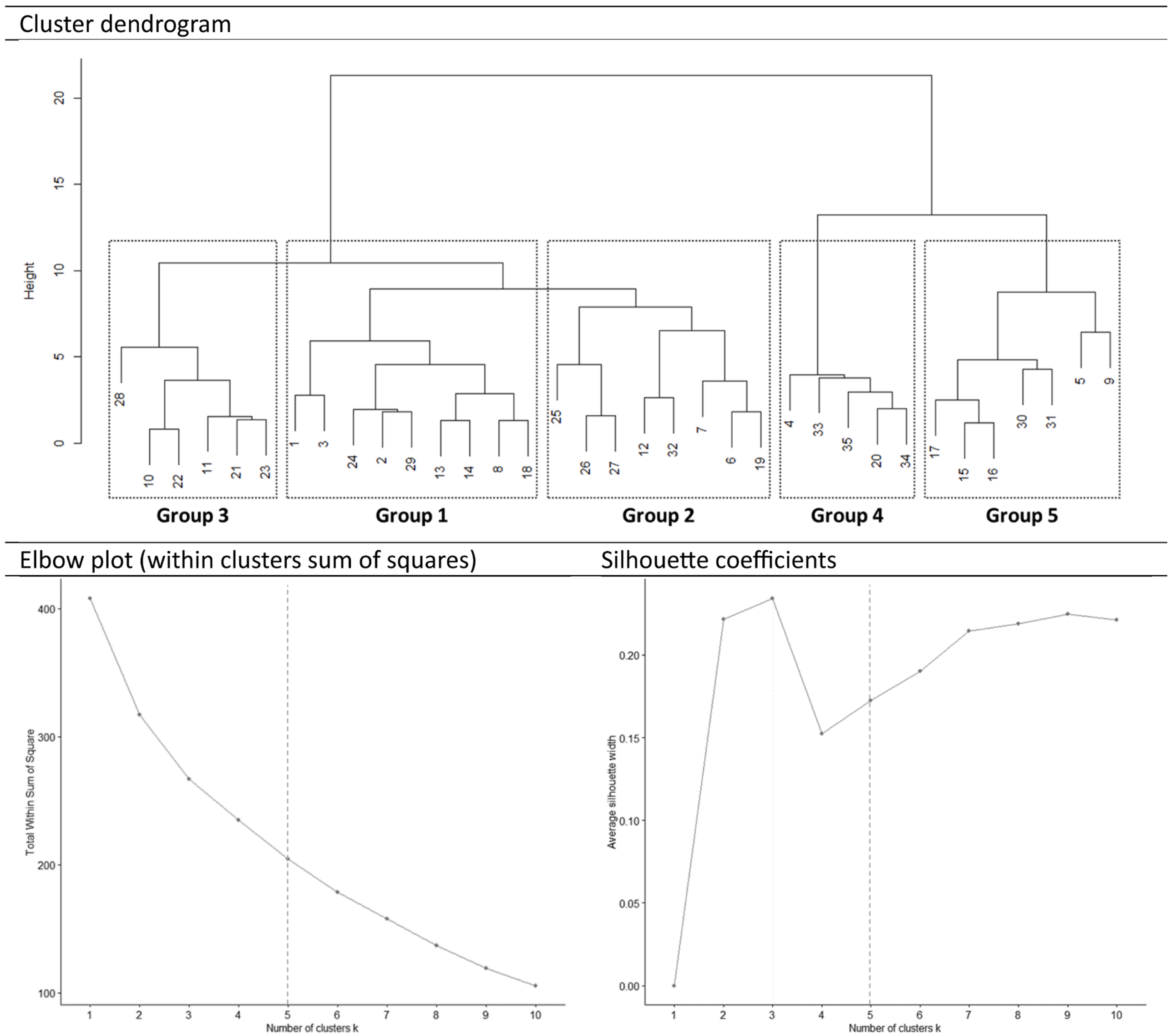
Appendix 1. Definitions and rationale for the selected occupational variables indicating heatwave vulnerabilities

Variable	Operational definition	Rationale for selection
Senior workers	Percentage of workers aged 55 and over (%)	Schulte et al. (2016)
Female workers	Percentage of female workers (%)	
Longer hours of work	Percentage of workers who work >52 h a week (%)	Spurgeon et al. (1997), Landsbergis (2003)
Standing time	Percentage of standing hours (%)	Gubernot et al. (2014)
Strenuous work	Importance of physical ability in performing duties (self-reported score; 0–100)	
Irregularity of work	Percentage of workers who work according to weather, work whenever there is work, or work only at a specific time of year (%)	Nilsson and Kjellstrom (2010), Gubernot et al. (2014), Schulte et al. (2016)
Job instability	Percentage of nonregular workers (%)	
Monthly income	Average log monthly income	Cutter et al. (2003)
Education	Average number of years of education	
Foreign workers	Percentage of foreign-born workers (%)	Schulte et al. (2016)
Tenure	Average number of years of service	Maeda et al. (2006), Gubernot et al. (2014), Schulte et al. (2016)
Insufficient safety information	Percentage of workers who are not well provided with information on the risk factors for the working environment related to health or safety (%)	Nilsson and Kjellstrom (2010), Gubernot et al. (2014), Schulte et al. (2016)

Appendix 2. Location map of the study area. Sixteen provinces and 225 cities in Korea excluding island areas (Jeju, Seogwipo, and Ulleung)



Appendix 3. Hierarchical clustering results and metrics for determining the optimal number of clusters



Note: Numbers in cluster dendrogram indicate: 1. Fire and emergency management engineers and safety professionals; 2. Police, fire fight and prison related workers; 3. Transport services workers; 4. Door to door and street sales related workers; 5. Crop growers; 6. Horticultural and landscape workers; 7. Livestock industry and stockbreeding related workers; 8. Forestry related workers; 9. Fishery related workers; 10. Die and mold makers, metal casting workers and forge hammersmiths; 11. Pipe and sheet metal makers; 12. Automobile mechanics; 13. Transport equipment mechanics; 14. Broadcasting and telecommunications equipment related fitters and repairers; 15. Construction structure related technical workers; 16. Construction related technical workers; 17. Construction finishing related technical workers; 18. Mining and civil engineering related technical workers; 19. Plumbers; 20. Other technical workers; 21. Metal casting and metal processing related operators; 22. Painting and coating machine operators; 23. Nonmetal products production machine operators; 24. Cooling and heating related equipment operators; 25. Automobile drivers; 26. Handling equipment operators; 27. Construction and mining machines operators; 28. Ship deck workers and related workers; 29. Water treatment plant operators; 30. Construction and mining elementary workers; 31. Loading and lifting elementary workers; 32. Deliverers; 33. Cleaner and sanitation workers; 34. Sales related elementary workers; 35. Meter reading, money collecting and parking controlling related workers.

Appendix 4. Cities in Korea with high or low concentrations of heatwave-exposed workers (by group), 2020

All		Group 1		Group 2	
Highest cities	LQ	Highest cities	LQ	Highest cities	LQ
Sinan	3.517	Geoje	3.376	Hampyeong	1.959
Cheongsong	3.366	Sinan	2.715	Hapcheon	1.843
Yeongyang	3.264	Taebaek	2.399	Hongseong	1.841
Bonghwa	3.083	Cheongsong	2.335	Okcheon	1.836
Boseong	2.966	Samcheok	2.315	Cheongyang	1.836
Lowest cities	LQ	Lowest cities	LQ	Lowest cities	LQ
Seocho	0.225	Jung (Seoul)	0.379	Seocho	0.234
Gangnam	0.231	Yongsan	0.459	Gangnam	0.243
Yongsan	0.310	Jinan	0.488	Yongsan	0.319
Jung (Seoul)	0.389	Seocho	0.489	Jongno	0.413
Jongno	0.392	Gangnam	0.492	Jung (Seoul)	0.415
Group 3		Group 4		Group 5	
Highest cities	LQ	Highest cities	LQ	Highest cities	LQ
Gwangyang	5.785	Muju	4.675	Sinan	7.420
Dangjin	5.078	Jangsu	4.142	Cheongsong	6.587
Pohang	4.413	Samcheok	4.005	Uiseong	6.530
Haman	3.965	Hwasun	3.709	Yeongyang	6.454
Goryeong	3.852	Yeongyang	3.687	Jindo	6.371
Lowest cities	LQ	Lowest cities	LQ	Lowest cities	LQ
Goseong	0.046	Seocho	0.351	Gangnam	0.106
Yongsan	0.060	Gangnam	0.398	Seocho	0.116
Inje	0.070	Yongsan	0.563	Yongsan	0.198
Gangnam	0.077	Songpa	0.569	Gwacheon	0.205
Hwacheon	0.086	Yeonsu	0.632	Mapo	0.247

Data availability

Data will be made available on request.

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