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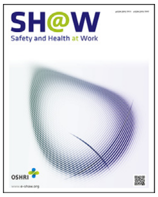

Original Article

Spatial Changes in Work Capacity for Occupations Vulnerable to Heat Stress: Potential Regional Impacts From Global Climate Change

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ABSTRACT

Background: As the impact of climate change intensifies, exposure to heat stress will grow, leading to a loss of work capacity for vulnerable occupations and affecting individual labor decisions. This study estimates the future work capacity under the Representative Concentration Pathways 8.5 scenario and discusses its regional impacts on the occupational structure in the Republic of Korea.
Methods: The data utilized for this study constitute the local wet bulb globe temperature from the Korea Meteorological Administration and information from the Korean Working Condition Survey from the Occupational Safety and Health Research Institute of Korea. Using these data, we classify the occupations vulnerable to heat stress and estimate future changes in work capacity at the local scale, considering the occupational structure. We then identify the spatial cluster of diminishing work capacity using exploratory spatial data analysis.
Results: Our findings indicate that 52 occupations are at risk of heat stress, including machine operators and elementary laborers working in the construction, welding, metal, and mining industries. Moreover, spatial clusters with diminished work capacity appear in southwest Korea.
Conclusion: Although previous studies investigated the work capacity associated with heat stress in terms of climatic impact, this study quantifies the local impacts due to the global risk of climate change. The results suggest the need for mainstreaming an adaptation policy related to work capacity in regional development strategies.

1. Introduction

Worldwide, countries experience the negative effects of climate change, and the intensity and frequency of these effects are steadily increasing. An analysis by the Korea Meteorological Administration (KMA) based on the Intergovernmental Panel on Climate Change's (IPCC) Representative Concentration Pathways (RCP) scenario predicts an average temperature increase of 3.7 °C in the Korean peninsula from 2081 to 2100 [1]. The number of heatwave days is expected to increase 4-fold from the current 10.1 days to 40.4 days per year, whereas the number of tropical nights is expected to increase 14-fold from 3.8 to 52.1 nights per year [1]. These changes will affect various aspects of human life and specifically climate change, which will have particularly harmful effects on working conditions, including workers' health and their economic prospects [2].

The negative effects of the increase in temperature, heatwaves, and tropical nights may affect worker heat stress and heat-related illnesses. The combined exposure to high-temperature environments and rigorous physical activity can cause heat injuries to workers [3]. Ultimately, heat stress at work because of exposure to excessive temperature and humidity can impair work capacity. Working conditions, which affect work capacity, vary according to the environment, notably the prevailing humidity, radiant temperature, air movement (wind speed), and air temperature [4]. Work-related factors such as intensity and speed can increase the risk of heat stress. Individual factors such as hydration, clothing, fitness level, and acclimatization can also influence the risk of heat exhaustion [5–8].

Adverse weather conditions are an occupational risk for those who perform intensive physical labor outdoors and are involved in an increasing number of workplace accidents and injuries [9].

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Frequent heat exposure at work can diminish physical and mental capacity, which consequently impairs overall work capacity [10]. Work capacity refers to the capacity of an individual's physical work performance [11]. It is influenced by various environmental factors, including humidity, airflow, and ambient temperature, as well as workers' physical health and work intensity. Recent discussions on work capacity have addressed potential reductions in labor productivity [2].

Previous studies on working conditions and the heat stress of workers have primarily used heat stress indexes such as the *Heat Index* from the United States National Weather Service, *Humidex* from the Meteorological Services of Canada, and the *wet bulb globe temperature* (WBGT) index [9]. The most widely used is the WBGT, which reflects the temperature perceived by humans. It was initially developed by Yaglou and Minard [12] of the United States Army and Marine Corps to evaluate heat-related illnesses [9,13,14]. Despite the potential for measurement errors and its limitations in incorporating individual factors such as clothing, the WBGT has been used to identify the relationship between external environmental factors and heat stress in workers. It has also been accepted by the International Organization for Standardization (ISO) 7243 (1989) and the American Conference of Governmental Industrial Hygienists as a preliminary tool in the evaluation of hot thermal environments [14].

Climate change and increasing temperatures will likely result in adjustments to the heat stress index, which will ultimately affect worker capacity. Based on ISO 7243 and the United States National Institute for Occupational Safety and Health (NIOSH) standards, Kjellstrom et al suggested an association between WBGT and work capacity [2]. The authors used the metabolic rate range from ISO 7243 to establish four work intensity levels covering 200–500 W. These four levels were further categorized by the industry type. Office and service industry workers had a work intensity of 200 W and manufacturing industry workers had an average work intensity of 300 W. The 400 W work intensity group included construction workers and those in the farming industry, whereas the 500 W group included workers engaged in heavy physical labor. Although Kjellstrom et al described the potential effect of climate change on workers and labor productivity, their classification of occupational types is unclear, and they were unable to distinguish sensitivities based on heat exposure and work intensity [2].

Occupations are classified based on similarities between workers' roles. Certain occupations are at a higher risk of exposure to high-temperature environments. This is likely to result in changes to local economies, as well as to industry and employment structures [15–17]. Regions with a high proportion of occupations that require frequent exposure to high-temperature environments will likely experience intensifying climate change effects, which can result in an overall deterioration of workplace environments and reduced productivity. These changes are also connected to the occupational structure of different regions, which can, in turn, affect the local economy. The occupational structure of a region is thus an important driving force for the region's economic development [18,19]. Specifically, if a local economy depends heavily on a business whose productivity is easily affected by climate change, it is bound to experience negative effects of reduced labor productivity [15]. Therefore, it is essential to examine the occupational structures of regions and identify the potential effect of climate change on work capacity.

Accordingly, this study identifies the potential reduction in regional work capacity by occupational characteristics and climate change. Subsequently, it examines the spatial patterns linking the changes in work capacity to the regional occupational structure.

2. Materials and methods

2.1. Framework

To identify the spatial changes in work capacity due to climate change, three indicators are combined in Fig. 1. The unit of analysis is the *si-gun-gu*, the basic spatial unit of local governments in the Republic of Korea. Two hundred and twenty-eight *si-gun-gu* were used, excluding four with no adjacent areas.

First, this study used the average regional WBGT, calculated as the climate change scenario from IPCC, as provided by the KMA [20]. The KMA calculates the WBGT based on Ono and Tonouchi's method [20,21]. The raw data were based on the daily maximum temperatures from June 1 to September 30 each year. Raw annual data were transformed into averages for the 2020s, 2030s, 2040s, and 2050s under the RCP 8.5 scenario of the IPCC. The WBGT of daily maximum temperatures was used because daily average temperatures do not reflect the tendency toward extreme labor conditions during summer, because a decrease in work capacity can occur at the hottest time of the day.

Second, occupations were classified using the three-digit level of the Korea Standard Classification of Occupation (KSCO) categories [22]. From these classifications, and based on vulnerability to heat exposure and work intensity, watt levels for each occupation were established using the Korea Working Conditions Survey (KWCS) variables [23]. Next, the association between WBGT and watts discussed by Kjellstrom et al and based on ISO and NIOSH standards was used to identify potential future work capacity loss by occupation type [2]. This loss was estimated for each decade until 2050.

Finally, the loss estimated in step 2 was analyzed in relation to the regional occupational structure in the Republic of Korea to identify the regions where work capacity loss would occur in clusters. Exploratory spatial data analysis based on local indicators of spatial association was adopted, as suggested by Anselin [24].

2.2. Measurements and data

2.2.1. Physical indicator

The KMA provided WBGT values, as derived from Equation (1), for the RCP 4.5 and 8.5 scenarios until 2100 [20]. In this study, daily data from June to September from the RCP 8.5 scenario were used to calculate the averages for each decade, which were subsequently employed as WBGT data.

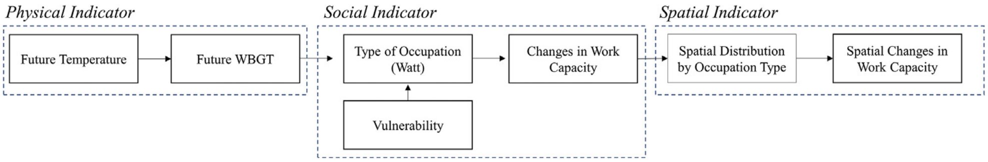


Fig. 1. Analytic framework.

$$WBGT = 0.735 \times Ta + 0.0374 \times RH + 0.00292 \times Ta \times RH + 7.619 \times SR - 4.557 \times SR^2 - 0.0572 \times WS - 4.064 \quad (1)$$

where Ta is the maximum temperature (°C), RH is the relative humidity (%), SR is solar radiation (KW/m^2), and WS is the wind speed (m/s).

2.2.2. Social indicator

Watt classifications, 100–500 W, represent the hourly work efficiencies under high-temperature conditions. However, the job classifications using the 100–500 W levels described by Kjellstrom et al are based on industry type [2]. They do not distinguish between occupation type and individual worker capacity. Additionally, this categorization is limited because it does not incorporate the differences between occupation types in the level of heat exposure, work environment, or work intensity.

These limitations underline the need to develop a method that considers exposure and sensitivity-related work environments for the occupation types in each watt level category. Because work environments can vary by occupation rather than by industry type, KSCO standards are used.

One hundred and forty-seven occupation types were established at the three-digit level, excluding military jobs. Work environment, work type, workplace, and risk factors vary according to the occupation type. Based on the KWCS results, watt level categorizations were developed to consider the factors that exacerbate worker heat exhaustion in high-heat environments.

The KWCS surveys the overall workplace environment by examining labor, employment, and occupation type, as well as exposure to risk factors and employment stability. Among the various physical work-related risk factors, this study evaluated high-temperature exposure to identify the factors that exacerbate heat exhaustion among workers in high-temperature environments. The seven variables listed in Table 1 were used as sensitivity factors associated with intensifying worker heat exhaustion. These sensitivity factors include musculoskeletal risk, such as tiring or painful positions, carrying or moving heavy loads, and repetitive hand/arm movements. Working at high speeds and having tight deadlines were other factors expected to affect performance speed.

The average score for each variable was calculated based on the three-digit classification and raw data collected from the third KWCS wave of 2011. Occupation types with fewer than 10 cases were eliminated because of potential representation bias. The seven sensitivity variables in Table 1 were converted using a weighted average and then used to determine the watt categories of occupation types. The weighted averages were calculated as the combined weighted average of the six variables and high-temperature exposure variables:

$$W = \frac{\alpha_1 x + \alpha_2 x + \cdots \alpha_n x}{\alpha_1 + \alpha_2 + \cdots \alpha_n} = \frac{\sum_{i=1}^{n} \alpha_i x}{\sum_{i=1}^{n} \alpha_i}, \quad (2)$$

Table 2
Weighted average of watt level classification criteria

Survey item	Score	Percentage	Watt criteria
All the time	7	100%	500 W
Almost all the time	6	85.71%	500 W
Around 75% of the time	5	71.43%	400 W
Around 50% of the time	4	57.14%	300 W
Around 25% of the time	3	42.86%	200 W
Almost never	2	28.57%	100 W
Never	1	14.29%	100 W

where α_i represents musculoskeletal risk factors and x indicates high-temperature exposure variables.

Using Equation (2), watt levels were established by taking the weighted average of the values of each raw data point from the KWCS. Then, the scores from “1” to “7” were converted into percentages, and the percentages of the weighted average values were used to determine watt level categories (Table 2).

The WBGT–work capacity relationship was determined using a non-linear graph proposed by the ISO and NIOSH. The WBGT–work capacity relationship estimation method suggested by Kjellstrom et al was applied [2]. The following equations were used to estimate the changes in work capacity according to future WBGT values:

$$500\ W = -0.1827X^3 + 18.051X^2 - 599.56X + 6696.9, \quad (3)$$

$$400\ W = -0.1655X^3 + 17.127X^2 - 594.08X + 6913.6, \quad (4)$$

$$300\ W = -0.1683X^3 + 17.653X^2 - 621.97X + 7369.4, \quad (5)$$

$$200\ W = -0.1655X^3 + 18.492X^2 - 692.03X + 8680.3. \quad (6)$$

These polynomial equations were used to predict changes in work capacity as a result of WBGT changes for each watt level corresponding to an occupation type. To identify the loss of work capacity at city, county, and district levels, the scope of loss according to the watt composition was calculated for each geographical area up to 2050 based on the number of employees in each occupation type in each area. Raw data were collected from the 2010 Population and Housing Census of Korea.

2.2.3. Spatial indicator

The local Moran's I statistic by Anselin was used to identify hotspots of significant work capacity loss [24]. This statistic can identify spatial clusters based on spatial correlation. The analysis classified the patterns of spatial association into the following four

Table 1
KWCS heat stress and sensitivity factors

Factor		Detail
Physical work-related risk factors		Level of heat exposure that results in sweating while not engaged in work
Sensitivity	Musculoskeletal risk factors	Degree to which tiring or painful positions are required to perform job tasks Degree to which carrying heavy loads is required to perform job tasks Degree to which moving heavy loads is required to perform job tasks Degree to which standing is required to perform job tasks Degree to which repetitive hand or arm movements are required to perform job tasks
	Performance Speed	Degree to which working at high speed is required to perform job tasks Degree to which working to tight deadlines is required to perform job tasks

categories: HH (high-high), high values surrounded by high values; LL (low-low), low values surrounded by low values; LH (low-high), high values surrounded by low values; and HL (high-low), low values surrounded by high values. The local Moran's I is calculated as per Equations (7) and (8):

$$I_i = \frac{x_i - \overline{X}}{S_i^2} \sum_{j=1, j\neq i}^{n} w_{ij}(x_i - \overline{X}), \tag{7}$$

where x_i is an attribute for feature i, $\overline{X}$ is the mean of the corresponding attribute, w_{ij} is the spatial weight between features i and j, and

$$S_i^2 = \frac{\sum_{j=1, j\neq i}^{n} w_{ij}}{n-1} - \overline{X}^2, \tag{8}$$

where n equals the total number of features.

3. Results

3.1. Future temperature and WBGT

The 10-year average values of daily maximum temperatures from June 1 to September 30 in the RCP 8.5 scenario were categorized for 228 units of analysis (*si-gun-gu*). Temperature and WBGT were estimated in accordance with the unit of analysis, using the temperature in the RCP 8.5 scenario provided by the KMA and WBGT according to Equation (1) [20]. The results are shown in Table 3. In general, temperature and WBGT are both expected to increase to significantly higher values than the average summer temperature in the Republic of Korea (23.6 °C) over the past two decades (1981–2010). The standard deviation of the average temperature among the 228 units of analysis (*si-gun-gu*) is below 2 °C.

3.2. Occupations with high risk of heat exposure

Table 4 displays the statistics of the variables used to classify occupation types at high risk of heat exposure. Of these, 28 had fewer than 10 observations and were excluded from the analysis. The average heat exposure score of the overall sample was 2.17, just above the “little to no exposure” level. Among the sensitivity variables, the average score for repetitive upper body movement was the highest at 4.19. The scores pertaining to standing, tiring, and painful positions were also relatively high.

Table 5 shows the occupation types included in each watt level, based on the criteria in Table 2. Two occupation types at the 500 W level had an average score of 3.94, indicating heat exposure for around half the workday. Four occupation types were at the 400 W level, with an average score of 3.51, corresponding to heat exposure for 25–50% of the workday. Most occupation types (67) were at the 100 W level, all registering little to no heat exposure throughout the workday. The average sensitivity values did not vary significantly by the watt level. Except for 100 W, the average values of the sensitivity variables fell within 25–50% of the workday.

Table 6 shows the occupation types for the 200–500 W levels, defined as occupations with a high risk of heat exposure. There were two managerial occupations at the 200 W level, the lowest risk of heat exposure. Craft and related trade workers (code 7XX); equipment and machine operators and assembly workers (8XX); and elementary workers (9XX) were also grouped at this level. Occupation types at the 400 and 500 W levels—with high risk of heat exposure—included machine operators and elementary workers working in construction, welding, machinery, metal, and mining industries. These involve strenuous physical activities and repetitive tasks, and individuals engaged in these are vulnerable to machinery operation-related high heat exposure.

Fig. 2 demonstrates the spatial distributions of the five occupation types classified according to heat exposure and sensitivity. These five groups were examined by the natural breaks method. The distribution of occupations vulnerable to heat exposure was concentrated in the southern capital region, central region, and southeastern coastal areas. Areas with high ratios of employees engaged in occupations vulnerable to heat exposure were located in the southwest and central east. Consequently, the future

Table 3
Temperature and WBGT under the RCP 8.5 scenario

		Average	Max	Min	*SD*[*]
Temperature (°C)	2020s	27.85	30.24	23.43	1.15
	2030s	29.35	31.63	24.81	1.17
	2040s	29.33	31.81	24.57	1.19
	2050s	30.30	32.76	25.80	1.14
WBGT[†] (°C)	2020s	26.66	28.48	22.11	1.27
	2030s	26.82	28.79	22.55	1.23
	2040s	27.52	29.39	23.15	1.20
	2050s	27.82	29.65	23.78	1.17

[*] *SD*, standard deviation.
[†] WBGT, wet bulb globe temperature.

Table 5
Occupation types by watt levels based on heat exposure and the six sensitivity variables

		100 W	200 W	300 W	400 W	500 W
Number of occupation types		67	23	23	4	2
Average sample size per occupation type		139.31	200.70	75.74	86.25	97.50
High-temperature exposure	Average	1.64	2.48	3.02	3.51	3.94
	Minimum	1.06	2.23	2.64	3.28	3.91
	Maximum	2.20	2.80	3.24	3.86	3.96
	Standard deviation	0.29	0.16	0.16	0.27	0.03
Average sensitivity	Average	2.48	3.20	3.45	3.72	3.69
	Minimum	1.47	2.16	2.16	3.39	3.46
	Maximum	4.33	4.05	4.40	4.07	3.91
	Standard deviation	0.58	0.48	0.54	0.32	0.32

Table 4
Statistics of occupation types with high risk of heat exposure

		Average score	Minimum score	Maximum score	*SD*[*]
Sample size by occupation type		134	10	1,616	242.94
Heat exposure		2.17	1.06	3.96	0.70
Sensitivity	Exhaustion, pain	3.02	1.56	4.74	0.74
	Moving people	1.44	1.00	4.07	0.39
	Moving objects	2.41	1.11	4.79	0.89
	Standing	3.58	1.62	5.38	1.04
	Repetitive upper body movement	4.19	1.94	6.02	0.87
	Work speed	2.80	1.59	4.36	0.60
	Tight deadlines	2.66	1.48	4.20	0.59

[*] *SD*, standard deviation.

Table 6
Occupation types with risk of high-temperature exposure (200–500 W)

KSCO code	High temperature (avg)	Musculoskeletal risk (avg)	Weighted value (W)	Classified Watts (W)	Occupation	KSCO code	High temperature (avg)	Musculoskeletal risk (avg)	Weighted value (W)	Classified Watts (W)	Occupation
120	2.493	2.556	0.486	200	Administrative and business support managers	620	3.167	3.583	0.684	300	Forestry-related workers
141	2.590	2.649	0.510	200	Construction, electricity, and production-related managers	721	2.945	3.626	0.639	300	Textile and leather-related workers
237	2.800	2.943	0.568	200	Aircraft pilots, ship engineers, controllers	730	2.963	3.524	0.636	300	Wood and furniture, musical instrument, and signboard-related trade occupations
286	2.373	2.988	0.484	200	Sports and recreation-related professionals	741	3.083	3.615	0.668	300	Die and mold makers, metal casting workers, and forge hammer smiths
441	2.482	3.318	0.523	200	Chefs and cooks	751	2.805	3.253	0.587	300	Automobile mechanics
611	2.765	2.975	0.563	200	Crop growers	773	3.169	3.760	0.696	300	Construction finishing-related technical workers
630	2.300	3.269	0.482	200	Fishery-related workers	792	3.167	3.607	0.685	300	Plumbers
710	2.591	3.431	0.552	200	Food processing-related trade workers	821	3.000	3.714	0.656	300	Textile production and processing machine operators
742	2.455	3.117	0.507	200	Pipe and sheet metal makers	822	3.083	3.869	0.684	300	Textile and shoe-related machine operators and assemblers
752	2.433	3.190	0.506	200	Transport equipment mechanics	831	3.095	3.129	0.640	300	Petroleum and chemical material processing machine operators
753	2.618	2.992	0.534	200	Machinery equipment fitters and mechanics	843	2.952	3.279	0.619	300	Nonmetal products production machine operators
762	2.592	3.033	0.531	200	Electricians	851	2.703	3.517	0.580	300	Machine tool operators
780	2.225	2.857	0.448	200	Video and telecommunications equipment-related fitters and repairers	854	2.640	3.614	0.572	300	Transport vehicle and machine-related assemblers
811	2.538	3.407	0.539	200	Food processing-related machine operating occupations	855	2.923	3.308	0.615	300	Metal machinery parts assemblers
823	2.237	3.417	0.476	200	Laundry-related machine operators	874	2.975	3.365	0.629	300	Handling equipment operators
842	2.609	3.460	0.557	200	Painting and coating machine operators	875	3.059	3.187	0.636	300	Construction and mining machine operators
864	2.437	3.368	0.516	200	Electrical, electronic parts, and product assemblers	899	3.133	3.667	0.682	300	Other production-related machine operators
892	2.432	3.587	0.526	200	Print and photo development-related machine operators	910	3.130	3.692	0.683	300	Construction and mining elementary workers
922	2.273	3.282	0.477	200	Deliverers	921	3.149	3.751	0.691	300	Loading and lifting elementary workers
930	2.283	3.572	0.492	200	Production-related elementary workers	991	3.242	3.290	0.681	300	Agriculture, forestry, and fishing-related elementary workers
941	2.647	3.283	0.555	200	Cleaning and sanitation workers	772	3.280	3.810	0.724	400	Construction-related technical workers
952	2.527	3.725	0.553	200	Food-related elementary workers	832	3.324	3.811	0.733	400	Chemical, rubber, and plastic production machine operators
953	2.292	3.196	0.477	200	Sales-related elementary workers	841	3.860	3.877	0.857	400	Metal casting and metal processing-related operators
221	3.000	2.757	0.597	300	Computer hardware and telecommunication engineering researchers	891	3.571	3.400	0.758	400	Wood and paper-related operators
612	3.243	3.220	0.676	300	Horticultural and landscape workers	743	3.956	3.638	0.859	500	Welders
613	2.897	3.020	0.592	300	Livestock industry and stockbreeding-related workers	771	3.914	3.739	0.858	500	Construction structure-related workers

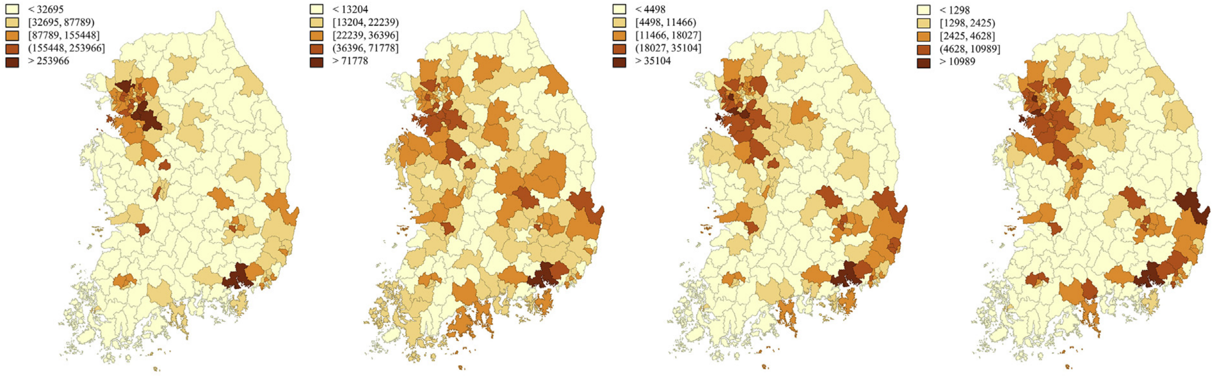
diminishing work capacity in each area was estimated using Equations (3)–(6) to determine work capacity by regional WBGT conditions and occupation types.

3.3. Predicted changes of work capacity in the future

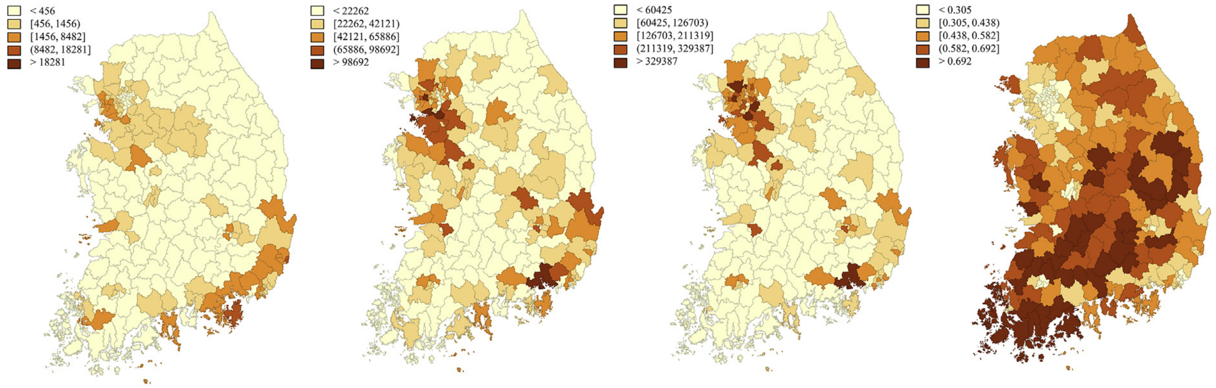
Fig. 3 demonstrates the previously suggested WBGT changes by region from 2020 to 2050 (a), by estimated reduction of regional work capacity considering the regional occupation structure (b), and by the ratio of decreasing work capacity to the number of laborers engaged in occupation types 200–500 W in each area (c).

Regarding regional WBGT changes, the regions with high temperatures are concentrated in the west in the 2020s and then gradually expand to the east and north. By the 2050s, most regions will find themselves in working environments different from those in the past, except for some mountainous regions in the central-south and northeast.

Regarding estimated work capacity reduction (b), by 2020, 15 areas will see a reduction of 100 to 500 workers, with a reduction of 500 to 1,000 workers in one area. The decreasing work capacity will mean drastic changes by 2030, with an estimated reduction of 100–500 workers in 54 areas, 500–1,000 in 40 areas, 1,000–3,000



(a) 100W (b) 200W (c) 300W (d) 400W



(e) 500W (f) 200W–500W (g) Total (h) 200W–500W/Total

Fig. 2. Spatial distribution of labor by occupation type.

in 19 areas, and more than 3,000 in 3 areas. This trend will further deteriorate by the 2050s and will be particularly conspicuous in terms of the spatial distribution. This trend becomes more evident in terms of the estimated ratios of working capacity to the number of 200–500 W laborers. These estimates were made in reference to the regional distribution of occupations in 2010, and thus, it is possible that the actual distribution may differ according to the evolution of the labor market and industrial and population structures. Nonetheless, the regional work capacity will be affected by rising temperatures because of climate change.

3.4. *Spatial clusters of diminishing work capacity*

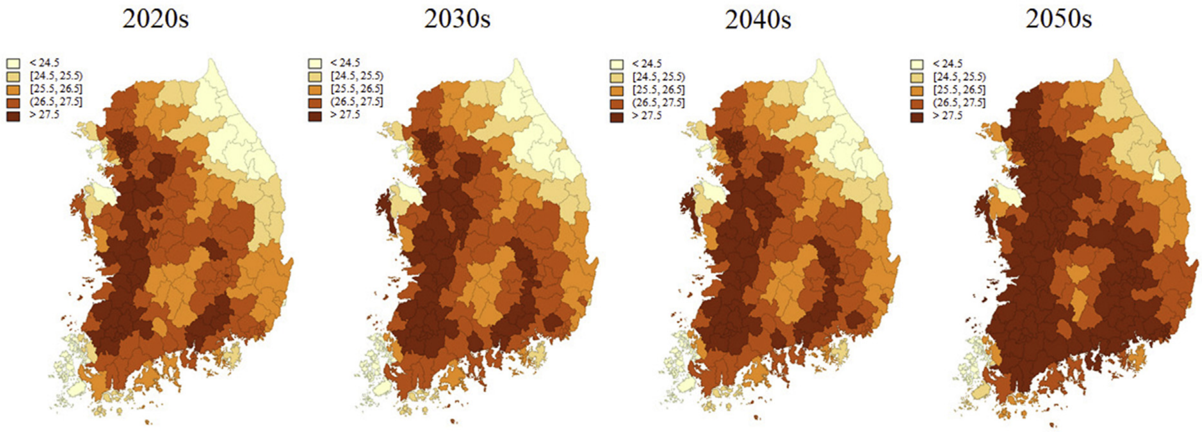
Table 7 and Fig. 4 demonstrate the spatial correlation between regions, showing the decreased work capacity previously seen in Fig. 3. The spatial relationship between areas was 30% according to the criterion of diminishing amount of work capacity and 41–55% according to the criterion of the ratio of work capacity decrease for workers in the 200–500 W classifications. Particularly, the analysis of the work capacity decrease ratio in reference to workers in 200–500 W occupations demonstrates a stronger spatial correlation.

Fig. 4a shows the results of spatial clustering after applying the local Moran's *I* value in reference to the absolute work capacity, which is expected to subsequently decrease. HH clustering is observed in certain areas in the southwest in the 2020s, which then expands into 3 to 4 spatial clusters over time. The formation of LL clusters is conspicuous in the east, contrary to the HH cluster. Fig. 4b shows the result of the work capacity decrease ratio relative to the number of 200–500 W workers. The pattern is similar to that of (a), which was measured in reference to the absolute capacity, but the spatial clusters expand mainly in areas with a higher number of 200–500 W workers.

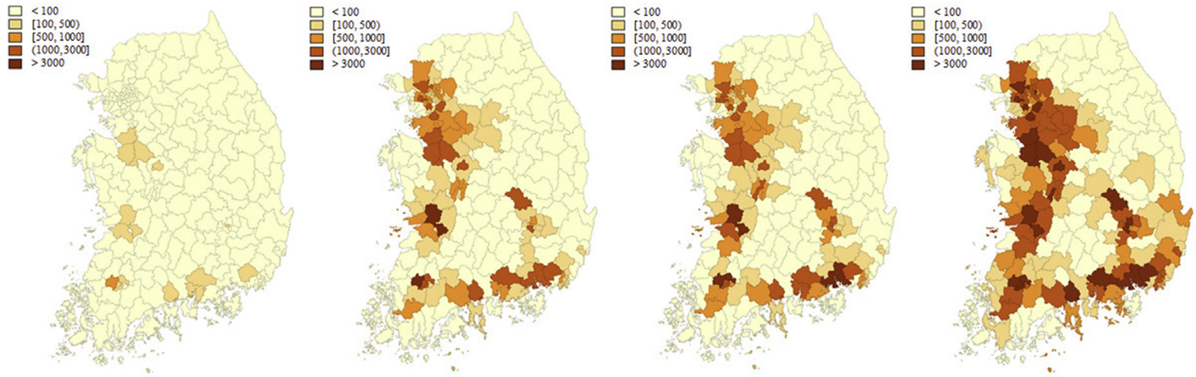
The results suggest that the increase in temperature triggered by climate change can affect the work environment and that regions relying on workers in occupations with high work intensity that are vulnerable to heat may become collectively vulnerable to the changing environment. This means the high-temperature environment caused by climate change is a matter concerning not only workers' working environment and work capacity but also the industrial structure. It thus requires solutions on a regional scale. In other words, a work capacity decrease refers to the amount of additional work capacity required to maintain the present production capacity and industrial structure form. If regions fail to secure an alternative workforce to compensate for the decreasing future work capacity, industrial production capacity will likely shrink. This will be particularly critical if industries in a similar situation form the major industrial group in an area, because this type of area can form spatial clusters and the entire region will likely suffer a consequent decrease. Considering it is difficult to change the industrial and occupational structures within a short period, our findings suggest that regions need to readjust their industrial and occupational structures over mid- or long-term periods.

4. Discussion and conclusion

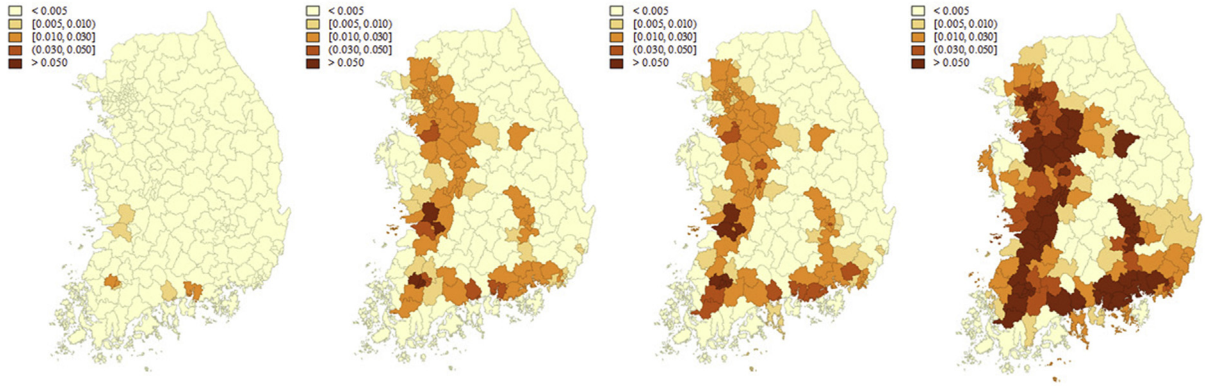
This study examined the predicted work capacity loss among Korean workers based on the steadily increasing WBGT arising from climate change. It evaluated the clustering of areas more susceptible to work capacity loss because of their occupational structures.



(a) WBGT



(b) Quantity of Diminishing Regional Work Capacity



(c) Ratio of Diminishing Regional Work Capacity

Fig. 3. Changes in WBGT and work capacity.

Based on these results, the policy implications aimed at adapting to climate change can inform the effects on individual worker productivity, work environment, regional occupational structure, and development strategies.

4.1. *Labor productivity and work environment*

Numerous predictions regarding the impact of climate change are based on IPCC's RCP scenario. The RCP 8.5 scenario assumes that the current greenhouse gas emission rate is maintained in the absence of an effective policy for reducing emissions and draws a realistic picture of our future in terms of adaptation. The analysis presented herein is also based on the RCP 8.5 scenario. The increase in temperatures in the Republic of Korea during June to September may lead to a significant loss of work capacity among workers whose jobs regularly require exposure to high temperatures.

As such, the diminished work capacity for occupations with a risk of high-temperature exposure can lead to decreased labor productivity. Of course, many factors affect labor productivity, including the amount of capital per worker and technological progress, but this study assumes that the factors affecting reduced work capacity are the same except for temperature. Thus, a

Table 7
Values of Moran's *I*

	Work capacity decrease	Ratio of work capacity decrease
2020s	0.295537	0.404673
2030s	0.317248	0.511260
2040s	0.308766	0.522468
2050s	0.309359	0.548367

reduction in a worker's work capacity means a reduction in labor productivity. The diminished work capacity of individual workers means more work hours will be required to accomplish the same amount of work.

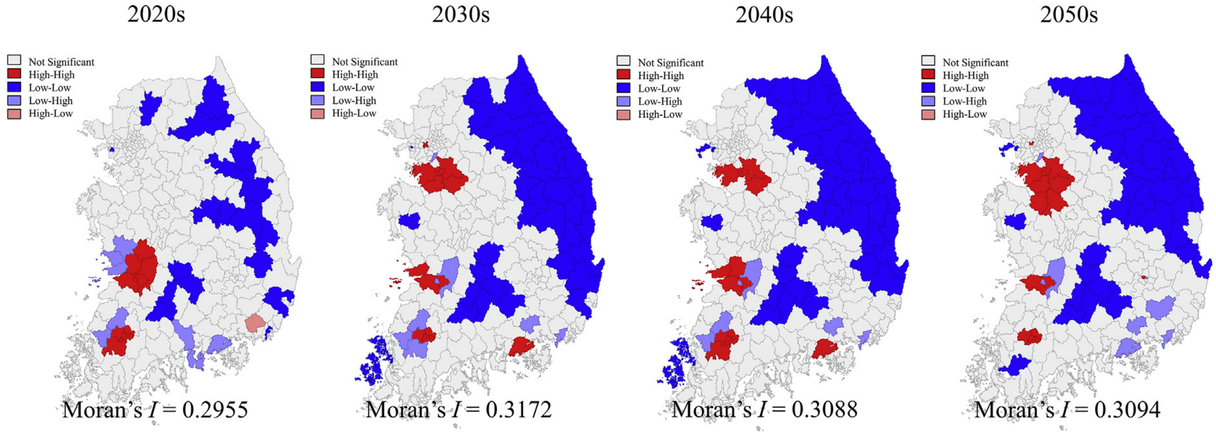
The issue of diminished work capacity necessitates climate change adaptation policies around employment conditions, wages, and work environment. For instance, policy measures should be implemented to protect workers from disadvantageous employment conditions, wage reductions owing to lowered productivity, and unsafe working conditions without scheduled breaks. In the absence of relevant standards and policies, unfair employment practices, such as replacing full-time positions with more part-time positions and hiring unskilled laborers at low wages, will proliferate in the labor market to maintain productivity. As such, new labor standards must be established to evaluate and monitor high-temperature work environments, scheduled breaks enforced to prevent heat injuries for workers, and employment and wage regulations implemented for occupations with a high risk of heat exposure.

The adaptation policies governing heat exposure can be incorporated into national employment standards and other relevant guidelines, as well as into occupational health and safety regulations. Employment standards and regulations must thus address the adjustment of scheduled breaks according to the risk of heat exposure and extreme weather (heat). Occupational health and safety regulations must define those occupation and workplace types with high risk of heat exposure, as well as the evaluation criteria. These regulations should further propose activities to monitor heat exposure, safety regulations, and heat injury prevention measures and must clearly define employers' responsibilities for maintaining appropriate and safe working temperatures.

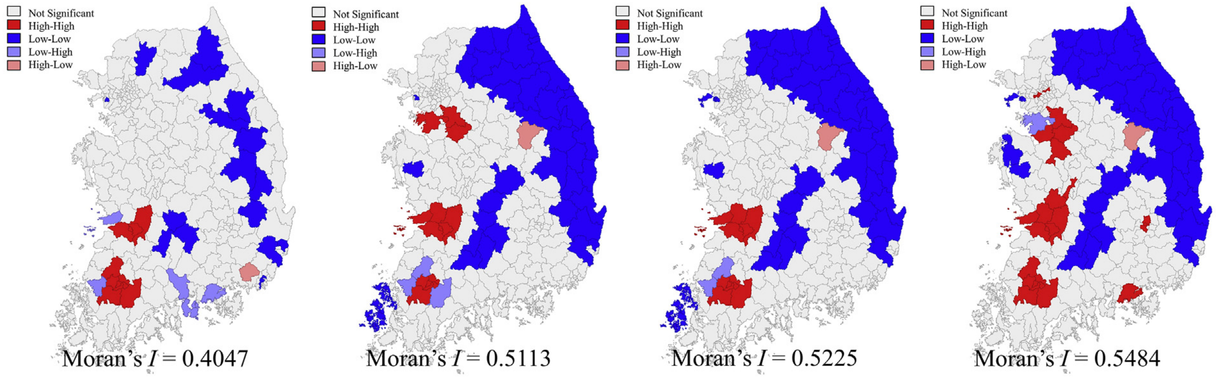
4.2. *Need for climate change adaptation policy for workers*

Although this study does not estimate thermal effects on the characteristics and physical capacities of individual workers, the potential impacts of global climate change on regional labor markets and groups of workers classified by occupations were analyzed. When considering these effects and climate adaptation, policy makers find it difficult to transform the structure of regional industries in a short period of time because workers' skills and work characteristics are already ingrained. Therefore, climate adaptation policy should include the creation of work environments aimed at reducing the thermal effect on individual workers.

The adaptive work environment should also be improved for individual workers. The duration of workers' activities involving



(a) Quantity of Diminishing Regional Work Capacity



(b) Ratio of Diminishing Regional Work Capacity

Fig. 4. Spatial clusters of diminishing work capacity.

continuous exposure to high temperatures should be measured, and information about heat stress should be conveyed to workers and managers in real time. In particular, in the case of manual workers, they can be exposed to various types of thermal environments with high temperatures depending on the working environment. Therefore, it is necessary to provide information about heat stress so that workers can increase their sensitivity to and recognize high temperatures.

Further, policies to strengthen the adaptive capacity of workers are needed. An individual toolkit to decrease body temperature should be provided, and there is a need for work safety facilities with air conditioning that are located close to the workers' workplace. In particular, manual workers may be subject to complex risks for musculoskeletal disorders and environmental threats from high temperatures; therefore, tools that provide workers support when performing simple and repetitive tasks are needed. In addition, precautionary training is required to prevent workplace risks caused by high temperatures in repetitive work environments.

4.3. Need for diversification of occupational structures and regional development strategies

Occupations with high risk of heat exposure also require diversification of occupational structures and regional development strategies. Ongoing discussions have resulted in the development of various theories, ranging from the economic base and growth pole theories to the more recent theories of diversity in regional industry structures, localized economies, and occupational structures. Although climate change can bring about changes in industry structures and other fundamental components of development strategies, discussions on the impact of climate change are just beginning.

Our results suggest important implications for establishing regional development strategies. Further, the regional industry and occupational structures are not easily changed, and their change is gradual based on mid-to-long-term development strategies. It would thus be prudent to start planning effective adaptation policy changes in connection with regional development policies to prevent a significant loss of work capacity owing to increasing temperatures.

Sustained low productivity would likely result in industries moving from areas with high risk of heat exposure to areas with lower risk. This move would have a significant impact on a local economy if an industry was highly specialized or was a core industry of the region. As a preliminary measure against these impacts, additional surveys of regional industry and occupational structures must be conducted and development strategies be tailored to meet the new requirements of climate change. To establish sustainable strategies that reflect the impacts of climate change, the diversification of occupational structures within regional base industries and sensitivities to the impact of climate change need to be thoroughly considered.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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The data that support the findings of this study are openly available in the Occupational Safety and Health Research Institute of Korea at http://www.kosha.or.kr/kosha/data/primitiveData.do.

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